TPOINT
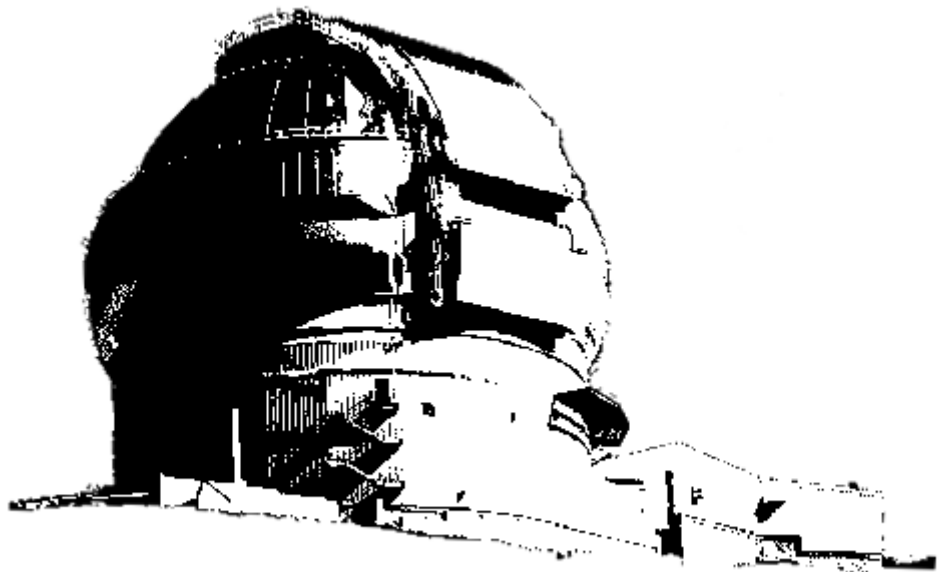
a telescope pointing analysis system

Version 18.13, for Unix
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TPOINT is licensed to:

Las Cumbres Observatory

Contents

Preface

TPOINT is a software system for analysing telescope pointing. It is a descendant of systems that have been in use at major observatories for many years, including optical, IR, mm and radio telescopes. Its origins go back to the author's work on the Anglo-Australian 3.9 m telescope in the 1970s.

The version to be described in this manual runs on Unix platforms; other versions exist which run on Microsoft Windows PCs.

Acknowledgements

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1 INTRODUCTION

TPOINT is a software system for analysing telescope pointing. It is used by observatories around the world: AAT, UKST, UKIRT, LPO, WIYN, ARC, Keck, JCMT, WHT, INT, NTT, VLT, Gemini, SOAR, GBT, LBT and many other major telescopes use TPOINT routinely to maintain their pointing models and to monitor performance.

Using TPOINT you can assess the potential for accurate pointing in your telescope and measure misalignments and flexures. The information TPOINT generates can be used in telescope control systems (TCSs) to improve setting accuracy and to enable good coordinates to be logged at any time. In addition, misalignments can be addressed mechanically, for example through adjustments to the polar axis. Using the sophisticated pointing models that can be developed with TPOINT, the best large telescopes deliver pointing accuracy below the 2 arcsecond level and some approach 1 arcsecond, roughly the diameter of the larger satellites of Jupiter. The best amateur telescopes can easily beat 1 arcminute, placing targets such as faint galaxies reliably in the center of even a high-power eyepiece.

1.1 Installing TPOINT on your Unix system

1.1.1 Standard distribution

The standard TPOINT package includes a makefile and all the files necessary to build an executable system, for a specific Unix. The only pre-requisites are the Unix operating system itself and the `Tcl/Tk` package, which is used for graphics. The package is in the form of separate files, either on a single ISO 9660 format CD-ROM or downloaded as a tar file. Installation is straightforward, and the makefile can easily be adapted should the default installation procedure not be ideal. This is how to install TPOINT:

1. If CD-ROM, mount it and either `cd` to it or copy the contents to a directory on the hard disk and `cd` there. If a downloaded tar file, extract its contents into a directory on the hard disk and `cd` there.

2. The documentation is supplied on a `.pdf` file. Copy it to an appropriate place on your system.

3. Review the makefile for compatibility with local conventions. By default, files will be placed in the directories `$HOME/bin` and `$HOME/etc/tpoint`, creating these directories if they do not already exist. If these destinations are not suitable, either edit the makefile, or alternatively when executing the makefile use `make INSTALL_DIR=` to override the `$HOME` default.

4. Invoke `make`.

5. Make sure the script `tpoint` and the executable `tpt` are in your path. (The makefile puts them in `$HOME/bin` by default.)

6. Should de-installation become necessary, type `make deinstall`.

To run TPOINT, `cd` to the directory you wish to work from and type `tpoint`. If the program fails to start, or if error messages appear during the start-up phase, or if the graphics commands fail to work, the things to check first are (a) paths, (b) the location and contents of the `tpoint.ini` file, (c) the location and contents of the `tpg.ini` file and (d) the existence, location and version of the `Tcl/Tk` software.

Details of how to use special versions of `tpoint.ini` and/or `tpg.ini` are given in Sections 8 and 8, near the end.

1.1.2   Full distribution

The full TPOINT distribution includes source code, not only for TPOINT itself but also for the SLALIB library that it uses. Each of these is supplied in source form as one or more `tar` files, on any appropriate media, for example CD-ROM. As for the executable system, the installation procedure is straightforward and not excessively automated:

1. Create separate directories for the various components:

`tpoint`	TPOINT (library and freestanding application)
`slalib`	Positional-astronomy library

2. As appropriate, and using conventional techniques, decompress and unpack the contents of the `tar` file(s) to the directories just created.

3. It is usually necessary to edit the makefiles to suit local directory structures and compiler options. Each makefile contains instructions on what to do. In most cases the changes are all near the beginning of the file. Note that `make`'s environment variables (for example `INSTALL_DIR` and the compiler options) can be specified on the command line, removing the need to modify the makefiles.

4. For SLALIB, `cd` to the appropriate directory and invoke `make`. If you are not using the `gcc` compiler, refer to the comments near the start of each makefile to see how to invoke `make` to use your choice of compiler. Then execute a `rehash`.

5. Go to the directory containing the TPOINT package and invoke `make` to create both the library and the executable system. (The same advice on running `make` as in the previous step apply here.)

6. Make sure the script `tpoint` and the executable `tpt` are in your path. (The makefile puts them in `$HOME/bin` by default.)

7. Should de-installation become necessary, type `make deinstall`.

To run TPOINT, `cd` to the directory you wish to work from and type `tpoint`. If the program fails to start, or if error messages appear during the start-up phase, or if the graphics commands fail to work, the things to check first are (a) paths, (b) the location and contents of the `tpoint.ini` file, (c) the location and contents of the `tpg.ini` file and (d) the existence, location and version of the `Tcl/Tk` software.

Details of how to use special versions of `tpoint.ini` and/or `tpg.ini` are given in Sections 8 and 8, near the end.

1.2   System overview

TPOINT is a straightforward, monolithic program which accepts commands from the keyboard. There is a simple but effective "command script" capability, and a log file can be produced, recording what operations were carried out and with what result. Pointing observations are input from ordinary ASCII files (as produced by a text editor) in flexible formats. Graphics output goes to a separate X window; TPOINT can be run on a non-X system but the graphics commands will not work. Some small star catalogs are provided, and some sample data. There is a straightforward text-based hierarchical help system.

1.3   How TPOINT is used

This is how to use TPOINT to investigate the pointing performance of your telescope:

1. Decide which place in the focal plane you want the pointing to refer to. Depending on the size of the telescope and the arrangements for viewing the field, this may be crosswires in an eyepiece, a particular pixel of a CCD, or an autoguider probe.

2. Point your telescope at a sequence of stars of known coordinates (so that the star image is on the crosswires etc.), and record the telescope readouts in a file.

3. Run TPOINT and invoke the INDAT command in order to read in the file of observations.

4. Invoke TPOINT's USE command to specify a likely pointing model for the telescope concerned. The extensive repertoire of TPOINT terms includes zero points, misalignments, flexures and so on as well as general-purpose harmonics and polynomials. There are standard models for both equatorial and altazimuth mounts which make it very easy to get started.

5. TPOINT's FIT command automatically calculates the optimum size for each term in the model, such that the overall model is the best possible fit to the observations.

6. Using TPOINT's graphics commands, the remaining pointing errors can be inspected.

7. If obvious non-random errors remain, additional terms can be added to the pointing model – and removed as necessary – and the fit repeated.

The final result estimates how well the telescope is capable of pointing, and what corrections need to be made to achieve this result. The coefficients which TPOINT produces (i.e. the numbers specifying the size of each pointing term) can be fed into the telescope's computer control system to improve the pointing. On small telescopes where there is no computer, they can be used to prepare tables of corrections for various parts of the sky. Another use of TPOINT is to identify opportunities for mechanical adjustment, for example enabling the polar axis of an equatorial mount to be set up accurately even on telescopes which cannot for some reason see the pole.

1.4   The TPOINT philosophy

Many observatories and telescope users have their own ways of fitting models to pointing observations, and in a numerical sense TPOINT may not produce results that are different or better. However, TPOINT is unusual (a) in that the telescope model can be changed during the interactive session and (b) in the variety of its graphical displays. These two features allow rapid exploration of the pointing possibilities of any given telescope and time after time leads to a better model than the one formerly used and to new insights into the telescope's behavior. TPOINT's ability to analyse data from multiple observing sessions, even where zero points etc. have changed, is another unique advantage.

The general approach taken by TPOINT is that as far as possible the telescope model should describe real effects (geometrical misalignments, well understood flexures, etc.), and empirical functions should be used only to mop up any remaining systematic errors. There is a school of thought which advocates using empirical functions (for example polynomials or spherical harmonics) for the whole job. However, the TPOINT approach has some advantages:

- Simple geometrical misalignments – for example a miscentered instrument on a mount which is located at a Nasmyth focus but is not coincident with the elevation axis – might require very complicated empirical functions but are simple to deal with analytically.

- Direct manipulation of certain geometrical terms while the telescope is in operation can be very useful. An important application of this technique is where a star is

switched from one instrument aperture to another simply by changing the collimation parameters. Another example is where the polar axis of a wide field telescope is routinely raised and lowered as a function of declination, to minimize the field rotation effects of differential refraction; the polar axis elevation parameter in the pointing model can simply be changed by the same amount and accurate pointing is maintained.

- A realistic model of a telescope frequently exposes mechanical deficiencies which can then be diagnosed and cured, or at least understood. Time- and temperature-dependent effects can be pinpointed and remedies sought.

- A realistic model is likely to require fewer terms, and the number of stars observed in a pointing test can be correspondingly smaller.

- Physically-based models are less likely to misbehave when extrapolating outside the area covered by the available test data.

In any case, the models available with TPOINT include an extensive range of empirical terms, giving the TPOINT user the best of both worlds. A good example of this is the AAT model, the terms of which are built into TPOINT as an example of what may be needed to tame a large equatorial with stringent pointing requirements. Though firmly based on well-understood geometrical misalignments and plausible tube flexure corrections, the AAT model also contains complicated harmonics describing what are believed to be flexures in the horseshoe and center section. These flexure models are encapsulated in two terms called HFX and HFD, which are always left at their nominal sizes and are not fitted when individual pointing tests are reduced. HFX and HFD were determined by empirical fits to a very large sample (well over 1000 stars) formed by superimposing the residuals from tests carried out over several years.

1.5   Running TPOINT

To run the TPOINT system from the Unix shell (typically running in an xterm window):

> `tpoint` *logfile initfile commands messages*

The four parameters – the log file, the initialization file, the command input device and the message output device – are all optional and are normally allowed to default, respectively, to the following files:

logfile	`/dev/null`
initfile	`tpoint.ini`
commands	`stdin`
messages	`stdout`

On termination, the log file, if one has been specified, contains a full record of the session, and includes extra information (e.g. correlations between pointing terms) too voluminous to be displayed on the screen during the run.

Each TPOINT command line consists of one or more fields separated by spaces. The first field, of up to 6 characters, is the **command name**, and specifies the action to be performed. The subsequent fields, if any, are the **arguments**. Where the arguments are numeric, free-format decoding is performed, and numbers may be entered in a wide variety of formats. The precise way the arguments are interpreted depends on the command in question.

TPOINT deals with all forms of input – both commands and the various sorts of data file – in a standardized way which allows for comments and blank lines to be used and provides consistent handling of lowercase information. Details of these conventions are given in Section 1.7.

To abort a command, type `Ctrl+C`. The command will terminate cleanly as soon as it can, and control will be returned to the operator ready for the next command. To exit normally from TPOINT, use the END command.

A full list of all TPOINT commands, in alphabetical order, is given in Section 7.1. A quick reference list can be found at the end.

Sequences of TPOINT commands can be executed from a text file called a *procedure library.* Standard TPOINT syntax applies to such libraries, which may thus contain blank lines and comments (beginning with '!') to enhance readability. In using procedures from a library, the following commands are involved:

`CALL` x	calls procedure x from the library
`.x`	same: shorthand for `CALL` x
`PROC` x	specifies the start of procedure x
`RETURN`	returns from and ends a procedure

Of these commands, CALL alone is permissible from the keyboard; PROC and RETURN are used only in library procedures.

A command `CALL` x (or $.x$) can optionally be followed by arguments, separated by spaces. The argument strings are then substituted into any macros $1, $2,...$n that are encountered during execution of the procedure, where n is the nth string after the procedure name.

The standard procedure library file is automatically loaded when TPOINT is started unless a different one is specified on the command line as described above. After loading the library, TPOINT automatically executes a 'CALL INIT'; the INIT procedure supplied in the standard library does nothing. Any procedure library loaded as part of start-up must contain an INIT procedure.

A private library can be loaded at any time during the TPOINT session by using the INPRO command. This supplements whatever has previously been loaded, so there is no need for private libraries to contain copies of the standard procedures – though this will do no harm. Indeed, a private library may contain only one procedure if desired, and each time it is reloaded that procedure will replace its previous version. The INIT procedure is not called when INPRO is used from the command line.

An INPRO command without arguments restores the original library, without any subsequent additions.

By default, procedure commands are not echoed on the screen; they can be made to appear by means of the ECHO ON command. The volume of messages output during the running of complicated procedures can be controlled by means of the MESLEV command. (This command can also be used from the keyboard, though suppressing messages during normal interactive use of TPOINT is not recommended.)

1.6   An example TPOINT session

A painless way to learn how TPOINT works is to reduce some real data, using one of the sample files. Proceed as follows. First start the system:

```
tpoint
```

There will be various announcements, followed by a `'*'` prompt. Read in the `ukst.dat` sample data file, which is from the 1.2 meter UK Schmidt Telescope at Siding Spring Observatory in Australia:

```
INDAT ukst
```

(You may need to specify a full pathname for the `ukst.dat` file.) The observations will be listed on the screen. Specify the standard geometrical model for an equatorial mount, and then fit the model to the data:

```
USE IH ID NP CH ME MA
FIT
```

The values of the pointing coefficients are reported, as well as the root-mean-square (RMS) error on the sky and the population standard deviation (PSD – an estimate of what the RMS would be if the number of stars was much larger). There is also information about which observation happens to have the most influence on the model, and whether it looks abnormal.) Plot the residuals (the pointing errors which remain after the TPOINT model has been applied):
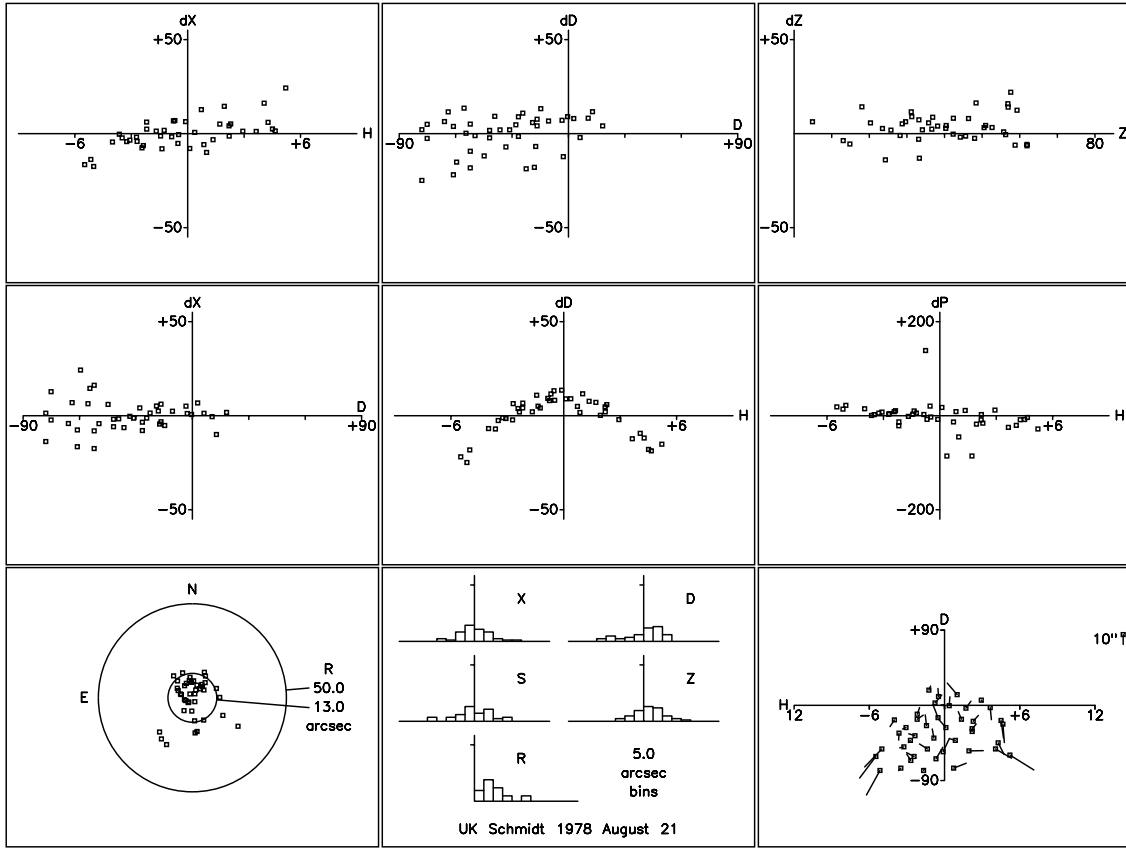
Figure 1: UK Schmidt Telescope, after fitting the standard 6-term model for an equatorial. The central plot is δ residuals against h, and is characteristic of fork flexure.

        CALL E9 (or its shorthand form .E9)

The resulting set of graphs is shown in Fig. 1, where the same residuals are displayed in a variety of ways (see Section 3.2). In this particular case, conspicuous systematic effects are present in the central plot, which is dD (declination residual) versus H (hour angle). The term FO (fork flexure, $\Delta\delta =$ FO $\cos h$) is a standard one for fork mounted telescopes and produces this characteristic pattern of residuals. Include the term in the model, fit again and plot the residuals:

        USE FO
        FIT
        .E9

See Fig. 2: that the RMS and PSD are much improved, and there are no obvious remaining systematic effects. This simple 7-term model is, in fact, the one used operationally.

This illustrates the general strategy for modeling a telescope from scratch. Begin by suitably preparing the TPOINT system and inputting the data. Then create a preliminary model consisting of the basic set of geometrical terms, and perform a fit:
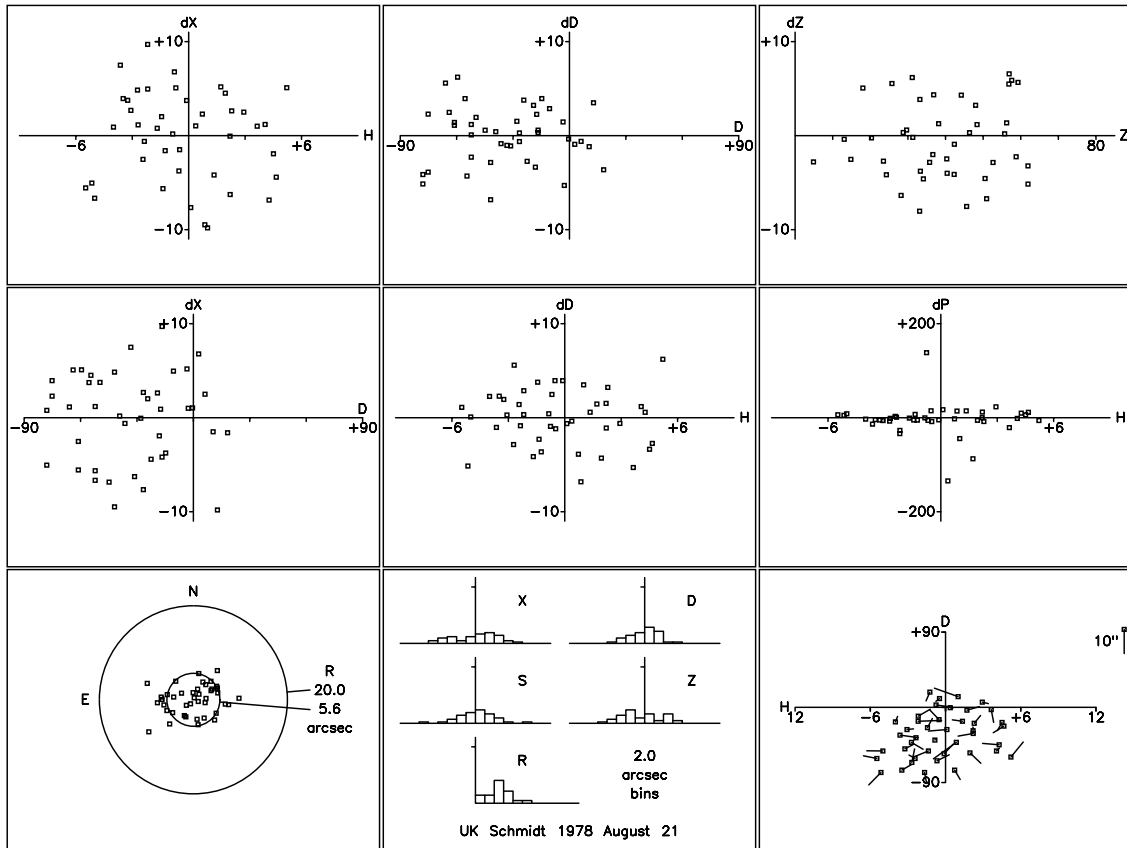
Figure 2: UK Schmidt Telescope, after adding the fork flexure term `FO` to the model.

```
       INDAT file
       USE IH ID NP CH MA ME          (for an equatorial)
    or USE IA IE NPAE CA AW AN         (for an altazimuth)
       FIT
```

(Procedures for setting up the basic equatorial and altaz models are also provided in the standard library: use `CALL EQUAT` or `CALL ALTAZ`.) The fit can be repeated until the solution settles down. Make a note of the population standard deviation, which is an indication of the general quality of the telescope before any modeling of flexure etc. The next step is to display the residuals graphically. A useful way to start is procedure E9 or A9 in the standard library:

```
       CALL E9                        9 favorite plots for an equatorial
    or CALL A9                        9 favorite plots for an altazimuth
```

(or use the shorthand form `.E9` etc.).

By means of the USE and FIT commands, try out extra terms to reduce any systematic errors. The simple Hooke's-law tube flexure term TF is frequently required; for fork and

yoke mounted equatorials try the fork flexure term FO, and for mounts with a declination axis supported at one end only (the English cross-axis and the German mountings are examples) try the declination axis flexure term DAF. When adding new terms, pay attention to the standard deviation of the new coefficient, the effect on other terms, and whether the population standard deviation has been reduced. Remove new terms if they are reported as being indistinguishable from existing ones, or if they lead to the appearance of messages warning that the fit is ill-conditioned. With the exception of the six standard geometrical terms, it is wise to reject any terms which are not at least 2 sigma in size. For each FIT, a table of the correlations between every pair of terms is output to the log file, for inspection after the TPOINT session; values close to unity show terms which are not easily distinguished given the current data.

Obvious "outliers" – observations much too far out to believe – can be temporarily excluded from the fit by using the command `MASK` n, where n is the observation number. The FIT command itself identifies the most likely candidate, while the OUTL command allows multiple outliers to be identified and MASKed.

More detailed advice is given in Section 2. But be sure to try TPOINT's auto-modeling facility:

    FAUTO

In many cases, this gives better results than a purely manual approach, especially as fine-tuning by hand can always be used as a second step.

The current settings of various internal parameters can be displayed as follows:

    SHOW

The list produced by SHOW includes the command names required to change the parameters, and is a useful guide to some of the facilities available within TPOINT. Here is an example:

```
    ADJUST: the model adjusts the telescope to fit the stars.
    APPEND: the next input file will overwrite the current data list.
    CAPT: caption plotting is enabled.
    CLRNG: the plotting zone is cleared before each plot.
    ECHO: library procedures execute silently.
    FITTOL: the ill-conditioning criterion is 0.001.
    FRAME: a frame will be plotted.
    MARKH: the marker height is 0.2.
    MESLEV: messages of all levels are displayed.
    messages of all levels are logged.
    PENS: current pens are 18, 5, 17, 12, 13, 2.
    PLTZ: the plotting zone is from (0.000, 0.000) to (1.000, 1.000).
```

```
    REPLEN: long reports are given in full.
    TXP: text precision is 2 (stroke).
    VT: the screen is assumed to be non-vt100.

    There are 42 observations in the data list, all active;
    equatorial mount has been specified.
```

1.7   Syntax

All TPOINT commands, procedure library records, star catalog records, model data records, and pointing data records, are subjected on input to a preliminary vetting and conditioning, as follows:

- Comments – records which are blank, or which have '!' as the first non-space character – are logged and displayed if appropriate but are otherwise ignored.

- Non-printing characters (TABs for instance) are replaced by single spaces.

- Leading blanks are eliminated as appropriate.

- Except within *string arguments*, lowercase characters are converted to uppercase.

- Multiple input lines can be concatenated using the backslash continuation character: if an input line ends with a backslash, that backslash and the subsequent newline are ignored.

String arguments are groups of characters delimited by pairs of either " or ' characters to show that they must stay lowercase. When a procedure library file is being input, string argument delimiters are left intact (to allow library commands to have lowercase arguments). For TPOINT commands, string argument delimiters are interpreted by the command routine itself. When star catalog files, pointing data files, and model data files are input, string argument delimiters are removed.

File names containing spaces can be used if they are surrounded by quote characters. TPOINT does not support procedure arguments that contain spaces etc.

2   MODELING

The pointing model is a sequence of terms selected from an internal repertoire. As well as explicitly formulated terms (geometrical effects for example) there is a generic type covering a wide range of polynomials and harmonics.

Terms can be **added** to the model by means of the USE command. For example, to add the terms for polar axis misalignment:

    USE ME MA

The USE command is also used to re-enable fitting after a FIX command.

Terms can be **removed** from the model by means of the LOSE command. For example, to drop the term PDH2:

    LOSE PDH2

The value of the coefficient of a single term can be **specified** by using the command:

    coeff val

where *coeff* is the name of the term and *val* the value in arcseconds. Thus to set the HA index error to +20″.7:

    IH 20.7

You would normally only do this for "FIXed" coefficients – ones excluded from fitting.

The current value of the coefficient of a single term can be **inquired** by entering a command consisting simply of the name of the term. For example, to display the current value of the declination index error, simply use the command:

    ID

The current model is **fitted** to the observations by means of the FIT command. Individual terms can be frozen at a particular value by means of the FIX command, or reinstated in the fitting by means of the USE command.

2.1   The pointing terms

The pointing terms fall into five categories – equatorial, altazimuth, general, special and generic. The model for any particular telescope may be a mixture of several of these types.

Some terms are functionally identical but have different names for historical, convenience or efficiency reasons. Most of them can be expressed using generic terms (polynomials and harmonics), but at the expense of clarity and slightly slower execution of the FIT and UNFIT commands. To find out what a given term means in a geometrical sense, refer to Section 7.2.

The following terms are most useful when modeling an **equatorial** telescope:

IH	index error in HA
ID	index error in Dec
NP	nonperpendicularity of HA and Dec axes
CH	nonperpendicularity of Dec and pointing axes
ME	polar axis elevation error
MA	polar axis error east-west
FO	fork flexure
DAF	flop of cantilevered Dec axis
DAB	bending of cantilevered Dec axis
HCES	HA centering error (sin component)
HCEC	HA centering error (cos component)
DCES	Dec centering error (sin component)
DCEC	Dec centering error (cos component)
DNP	dynamic nonperpendicularity
X2HC	$\cos(2h)$ term EW
A1H	HA change supplied through auxiliary reading 1
A1X	EW change supplied through auxiliary reading 1
A1D	Dec change supplied through auxiliary reading 1
A2H	HA change supplied through auxiliary reading 2
A2X	EW change supplied through auxiliary reading 2
A2D	Dec change supplied through auxiliary reading 2

The following terms apply to **altazimuth** telescopes:

IE	index error in elevation
IA	index error in azimuth
CA	nonperpendicularity of elevation and pointing axes
AN	NS misalignment of azimuth axis
AW	EW misalignment of azimuth axis
NPAE	nonperpendicularity of azimuth and elevation axes
NRX	horizontal displacement of Nasmyth rotator
NRY	vertical displacement of Nasmyth rotator
CRX	altazimuth coudé NS displacement
CRY	altazimuth coudé EW displacement
ACES	Az centering error (sin component)
ACEC	Az centering error (cos component)
ECES	El centering error (sin component)
ECEC	El centering error (cos component)
A1A	Az change supplied through auxiliary reading 1
A1S	LR change supplied through auxiliary reading 1
A1E	El change supplied through auxiliary reading 1
A2A	Az change supplied through auxiliary reading 2
A2S	LR change supplied through auxiliary reading 2
A2E	El change supplied through auxiliary reading 2

The following **general** terms may apply to any telescope:

TF	tube flexure – $\sin \zeta$ law
TX	tube flexure – $\tan \zeta$ law
FLOP	constant vertical displacement

There are several types of **special** term.

The first type of special term is those belonging to a **particular telescope**: the AAT in most cases, for historical reasons. These terms are included in TPOINT mainly as examples of what is likely to be involved in improving the pointing model for any large telescope as experience builds up:

ZH	AAT HA Z-gear effect in HA
ZE	AAT HA Z-gear effect in polar axis elevation
HF	AAT main east-west horseshoe flexure
HGES	36^m gear error in HA – sin
HGEC	36^m gear error in HA – cos
DGES	$9°$ gear error in Dec – sin
DGEC	$9°$ gear error in Dec – cos
TFP	AAT tube flexure – non-Hooke's-law term
HFX	AAT residual horseshoe east-west
HFD	AAT residual horseshoe north-south
CD4A	AAT coudé 4 collimation error A component
CD4B	AAT coudé 4 collimation error B component
CD5A	AAT coudé 5 collimation error A component
CD5B	AAT coudé 5 collimation error B component
AWGS	Gemini South azimuth axis tilt EW

The following special terms implement simplified **approximate** formulas and are included to match use of these formulas in control system software. An example is CA/CAL: the former is the nonperpendicularity of the telescope or antenna boresight to the elevation axis while the latter is just $\Delta A = -\mathrm{CA}\sec E$.

ANL	like AN but using simplified $\Delta A, \Delta E$ formulas
AWL	like AW but using simplified $\Delta A, \Delta E$ formulas
CAL	like CA but using a simplified ΔA formula
CHL	like CH but using a simplified Δh formula
MAL	like MA but using simplified $\Delta h, \Delta \delta$ formulas
MEL	like ME but using simplified $\Delta h, \Delta \delta$ formulas
NPL	like NP but using a simplified Δh formula
NPAEL	like NPAE but using a simplified ΔA formula
TXL	like TX but working in elevation rather than zenith distance

Two special terms provide for the case where there is an instrument rotator and the *pointing origin* (i.e. the image location) is not at the rotator axis:

POX	the x-coordinate of a pointing origin on an instrument rotator
POY	the y-coordinate of a pointing origin on an instrument rotator

To be able to solve for the POX and POY coefficients (see Section 5.12) requires observations at a variety of rotator position angles. This happens naturally the case of an altazimuth telescope if the rotator is being driven to maintain a given field orientation. TPOINT supports rotators at difference foci: mounted directly on the telescope, such as at Cassegrain or prime docus, or at a Nasmyth or coudé focus. The rotator angle is supplied in degrees as auxiliary reading #1. The rotator location, and the telescope type, are specified by "option" records in the data file that is read in by the INDAT command.

There are three types of **generic** (i.e. not individually named) term, where the name of the coefficient spells out the required formula. The most important generic terms are polynomials and harmonics.

Polynomial terms have names of the form:

$$\mathrm{P}rc\,[\;i\,[\;c\,[\;i\,]\;]\;]$$

For example, a term PXH2D1 would model an effect which produced an east-west shift (X) proportional to $h^2\delta$ (H2D1).

The initial $'\mathtt{P}'$ identifies this generic term as a polynomial.

The r field describes the result, and is one of the following:

H	result is in hour angle
X	result is east-west
D	result is in declination
U	result tilts polar axis up/down
L	result tilts polar axis left/right
P	result changes HA/Dec nonperpendicularity
A	result is in azimuth
S	result is horizontal
Z	result is in zenith distance (sky)
E	result is in elevation (mount)
N	result tilts azimuth axis north/south
W	result tilts azimuth axis east/west
V	result changes Az/El nonperpendicularity

(The distinction between *mount* and *sky* is important only for the "generalized gimbal" case. This will be dealt with in Section 5.

The two ci fields indicate the independent variables and their powers. Each i is in the range 0–9; each c can be any of:

H   hour angle
D   declination
A   azimuth
Z   zenith distance (sky)
E   elevation (mount)
Q   parallactic angle

Trailing ci or i fields, if omitted, default to unity. For example, a change in HA proportional to HA (i.e. a scale change, such as might be necessary with a roller-driven encoder) can be produced by using the term PHH.

Harmonic terms have names of the forms:

H $r\,f\,c\,[\,i\,]\,[\,f\,c\,[\,i\,]\,]$

or   H $r\,f\,c\,[\,i\,[\,i\,[\,i\,]\,]\,]$

For example, a term HXSH2 would model an effect which produced an east-west shift (X) proportional to sine (S) of $2h$ (H2).

The initial $'H'$ identifies this generic term as a harmonic.

The r and c fields describe the result and an independent variable respectively, and are as for polynomials, above.

Each fci, $fcii$ and $fciii$ field indicates a function of an integer multiple of an independent variable c. The f field is either S for sine or C for cosine. Each i is normally in the range 0–9, making available frequencies from zero to 999 cycles per revolution in the case of simple one-coordinate harmonics and, in the case of compound two-coordinate harmonics, 0–99 for the first angle and 0–9 for the second. An omitted i defaults to unity, as does an omitted trailing fci. As a special case, the integer can appear as a single $'%'$ character, denoting one-half. This allows one-cycle-per-two-revolutions effects to be modeled, such as might occur in ball or roller bearings.

Auxiliary terms, less commonly used than the other two types of generic term, simply apply a correction proportional to one of the *auxiliary readings.* They have names of the form:

A $n\,r$

For example, a term A2E would model an effect which produced a correction to mount elevation proportional to auxiliary reading #2.

The initial $'A'$ identifies this generic term as an auxiliary.

The n and r fields identify which of the three auxiliary readings is to be used and what is to be adjusted. The decimal number (n) is 1-99, and the same result codes (r) are used as for polynomials and harmonics.

A variant, called "vector auxiliaries", allows a single coefficient to be fitted using two auxiliary readings and delivery a vector result of some kind. For example, if basis function values for corrections in azimuth and elevation are supplied as auxiliary readings #3 and #4, the single term A3A4E can be used.

2.2   Sizes of coefficients

The mathematical expressions used by TPOINT are rather simple and designed to give results of adequate accuracy when not too close to the pole of the mounting and *when the pointing errors of the telescope are small.* Flexures and misalignments of up to a few arcminutes are unlikely to give problems; they will not interact significantly with one another, and will be calculated by TPOINT to sufficient accuracy. However, terms with larger coefficients may not be so well-behaved, especially near a pole.

A particular source of problems in practice is collimation error, the non-perpendicularity of the chosen pointing axis with respect to the declination or elevation axis of the mounting. If the measuring device – eyepiece, autoguider probe, CCD, TV camera etc. – is offset too far, there may be unmodeled pointing errors due to such effects as optical distortion. The best plan is to ensure that the measuring device is offset no more than a few minutes of arc. If this is impossible, and alternative is to pre-process pointing observations to remove the bulk of the offset before the TPOINT run. This might involve rigorous calculation of the tangent-plane projection and optical distortions.

These difficulties all go away if the "rigorous fitting" option is used. This will be covered later, in Section 5.10.

2.3   Saving models

Commands are provided for writing the current model to a file, and for replacing the current model with one read from such a file:

> OUTMOD *file* [S]   write [session] model to a file
> INMOD *file*   read model from a file

where *file* is the name of the file containing the model. As well as providing long-term storage for models, the file may also be read by programs external to the TPOINT system. (For the case where the external program is a telescope control system, OUTMOD's S option omits terms not normally needed for that application, namely POX, POY and any data subset terms – see Sections 5.12 and 5.8.) In addition to the model information required by INMOD, the file contains the current caption and the basic statistics which relate the model to the current data list. The INMOD command ignores these latter items.

The file consists of variable length formatted character records. The order of records within the file is:

> caption record
> method, statistics and refraction record
> term records (one per term in the model)
> end record

Here is an example file:

```
AAT␣␣f/15␣␣1979/06/11
T␣␣␣49␣␣␣1.1206␣␣␣52.015␣␣-0.0624␣␣␣2.0116
␣␣IH␣␣␣␣␣␣␣+174.7543␣␣␣␣␣␣1.18854
␣=ZH␣␣␣␣␣␣␣␣␣+3.5100
␣␣ID␣␣␣␣␣␣␣␣␣+23.0464␣␣␣␣␣␣0.35693
&=HFX␣␣␣␣␣␣␣␣+1.0000
&=HFD␣␣␣␣␣␣␣␣+1.0000
&␣HF␣␣␣␣␣␣␣␣␣-18.7283␣␣␣␣␣␣0.48982
&␣X2HC␣␣␣␣␣␣␣-3.1122␣␣␣␣␣␣0.26477
&␣NP␣␣␣␣␣␣␣␣␣+2.9636␣␣␣␣␣␣0.79658
&␣CH␣␣␣␣␣␣␣␣␣-18.6889␣␣␣␣␣␣1.20785
␣=ZE␣␣␣␣␣␣␣␣␣+0.7000
&␣ME␣␣␣␣␣␣␣␣␣+58.2504␣␣␣␣␣␣0.43977
&␣MA␣␣␣␣␣␣␣␣␣+2.9518␣␣␣␣␣␣0.24207
␣␣TF␣␣␣␣␣␣␣␣␣+8.9655␣␣␣␣␣␣0.54629
&␣TFP␣␣␣␣␣␣␣␣+1.1686␣␣␣␣␣␣0.47733
END
```

The **caption** record can be up to 80 characters long.

The **method, statistics and refraction** record can be read with a C `scanf` format string of `"%c %5d %9lf %9lf %9lf %9lf"` or a FORTRAN `FORMAT` specification of (`A1, I5, F9.4, F9.3, 2F9.4`). The fields are:

method: T or S
number of active observations
sky RMS (arcseconds)
refraction constant A (arcseconds)
refraction constant B (arcseconds)
sampled PSD (arcseconds, may be absent)

A method of ′T′ means that the model corrects the telescope readings, whereas ′S′ means that the model is applied to star positions to predict the required telescope setting.

Each **term** record can be read with a C `scanf` format string of `"%c %c %8s %10lf %12lf"` or a FORTRAN `FORMAT` specification of (`2A1, A8, F10.4, F12.5`). The fields are:

            chained/parallel flag
            fixed/floating flag
            term name
            coefficient value
            coefficient sigma

The chained/parallel flag is either a space (for "chained" terms, ones which are computed from the position as affected by all previous terms; see Section 5) or an ampersand (for "parallel" terms: members of a group all computed from the same starting position). The fixed/floating flag is either a space (for coefficients that are to be fitted) or an equals sign (for coefficients of fixed value). The term name and the coefficient value and sigma have their normal meanings.

The **end** record consists of the string 'END'. Reading programs should also interpret end-of-file as equivalent to an end record.

A further command:

        OUTMEX *file*

writes the same information (plus some additions) but in the form of a single line of fields separated by '|' (vertical bar) characters. This can be read directly by spreadsheet applications such as Microsoft Excel. The technique is particularly suited to studying how the pointing performance (in particular the values of particular model coefficients) is changing over time.

The order of fields in the OUTMEX output record is the same as in the OUTMOD file. The additional fields ouput by OUTMEX are the components of the sky RMS in the four directions (east-west, north-south, left-right and up-down) and a list of the stars that were excluded. The four RMS components immediately precede the sky RMS in the statistics portion of the record:

            method: T or S
            number of active observations
            EW RMS (arcseconds)
            NS RMS (arcseconds)
            LR RMS (arcseconds)
            UD RMS (arcseconds)
            sky RMS (arcseconds)
            refraction constant A (arcseconds)
            refraction constant B (arcseconds)
            sampled PSD (arcseconds, may be blank)

At the end of the OUTMEX record is a list of MASKed stars, in place of the 'END' record output by OUTMOD. (MASKed stars are ones you have elected to exclude from the fit.)

2.4   RMS and PSD estimates

It is important to understand that the sky RMS figures which TPOINT produces using the FIT command (also OUTMOD and OUTMEX) are *a posteriori* and may not be realized in practice. They do not take into account long term stability, the effectiveness of any pre-observing calibration procedures, the correctness of the implementation of the model within the telescope or antenna control software, or the ability of the user interface to give the astronomer access to the available performance.

Moreover, the reported sky RMS values are optimistic in cases where a large model is fitted to a small number of observations. To take this into account, the FIT command also reports the more honest statistic "population standard deviation", obtained as follows. Writing n for the number of floating coefficients (ones not marked $'='$) in the pointing model, ρ for the sky RMS and o for the number of active observations, the PSD is estimated as $\sigma = \sqrt{\rho^2 o/(o - n)}$. The "sampled PSD" produced by the SAMSIG command gives an even more honest result, by using the residuals obtained from models where the observation concerned has been excluded from the fit (a procedure known as "jackknifing"). If SAMSIG has been run, this sampled PSD will be present in the OUTMOD and OUTMEX output.

3   GRAPHICS

TPOINT has the following repertoire of graphics commands:

CAPT	enable/disable plotting of caption
FRAME	enable/disable plotting of graph frame
G	plot residuals in one coordinate against another
GAM	look for changing polar/azimuth axis misalignment
GC	special functions: clear screen, write hardcopy file
GDIST	plot error distributions
GHYST	look for hysteresis
GMAP	plot error vectors on cylindrical projection
GSCAT	plot residuals as a scatter diagram
GSMAP	plot error vectors on azimuthal projection
MARKH	specify marker size
PENS	specify pens for lines and text
PLTOF	close plotting window
PLTON	open plotting window
PLTZ	specify plotting zone

The PLTON command opens a plotting window which can optionally be named. The various graph plotting commands are then available: G, GAM, GDIST, GHYST, GMAP, GSCAT and GSMAP. Sample graphs from each of these commands can be found in Figs. 3 and 4.

PLTZ is useful for displaying several small graphs at once instead of one full-size graph; GC can be used to clear the whole screen beforehand. The PLTOFF command closes the current plotting window and reverts to the earlier one, if any.[1] The remaining commands – CAPT, FRAME, MARKH, PENS – are used either for reducing plotting time, or for achieving special effects for demonstration and publication purposes. They can be ignored by novice users.

Multiple plotting zones are supported, allowing several plots to be displayed at once. The current plotting zone is specified by the PLTZ command:

	PLTZ	use full display surface
or	PLTZ name	use named region
or	PLTZ x1 x2 y1 y2	use numerically specified region

The predefined zone names specify regular subdivisions of the display surface:

---

[1] In most TPOINT sessions there is no need to use PLTON and PLTOFF; a graphics window is, if necessary, opened automatically if there is any plotting to be done, and closed again when TPOINT is terminated.

T
B

L	R

TLQ	TRQ
BLQ	BRQ

TL	TC	TR
CL	CC	CR
BL	BC	BR

If numeric parameters are supplied, they describe directly the region of the display surface which is to contain the plotting zone. The numbers are the two X extremes and the two Y extremes respectively, in units where the corresponding dimension of the display surface is unity. All four numbers are required. Irrespective of the shape of the zone and how it was specified, plotting will actually occur in a zone of the standard aspect ratio centered within this area.

3.1   Using the G... commands

The commands in TPOINT which plot graphs all have names beginning with G. The most important one for deciding what terms to add to the model is called simply **G**, and plots one component of the residuals against one coordinate. It has the following syntax:

> G *ydata xdata* [*scale*]

The argument *ydata* specifies which component of the residuals is to be plotted:

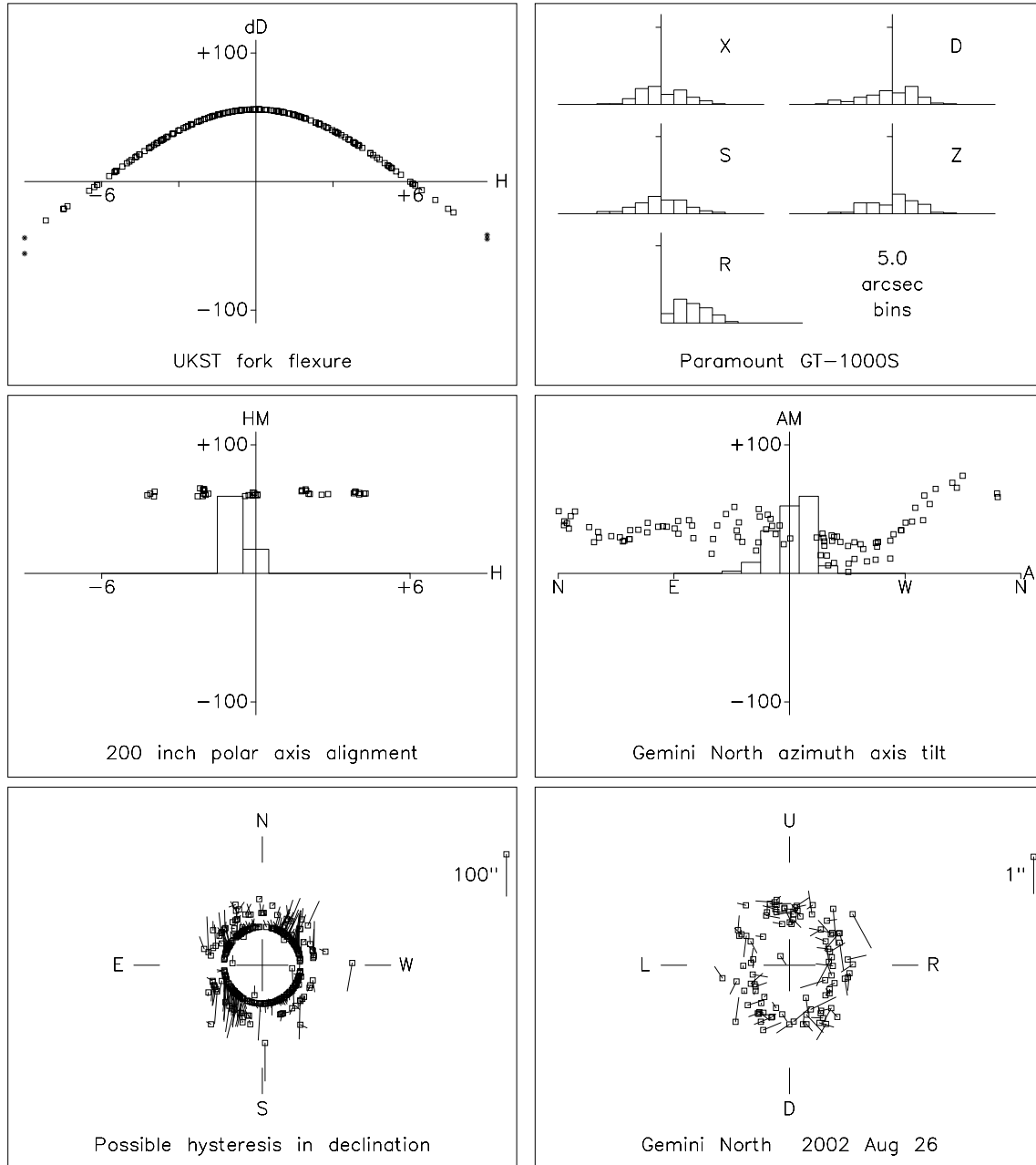|	
H	in hour angle
X	east-west
D	in declination
P	corresponding to HA/Dec nonperpendicularity
A	in azimuth
S	horizontally

Figure 3: Example plots using the commands `G D H` (top left), `GDIST` (top right), `GAM E` (center left), `GAM A` (center right), `GHYST E` (bottom left) and `GHYST A` (bottom right).
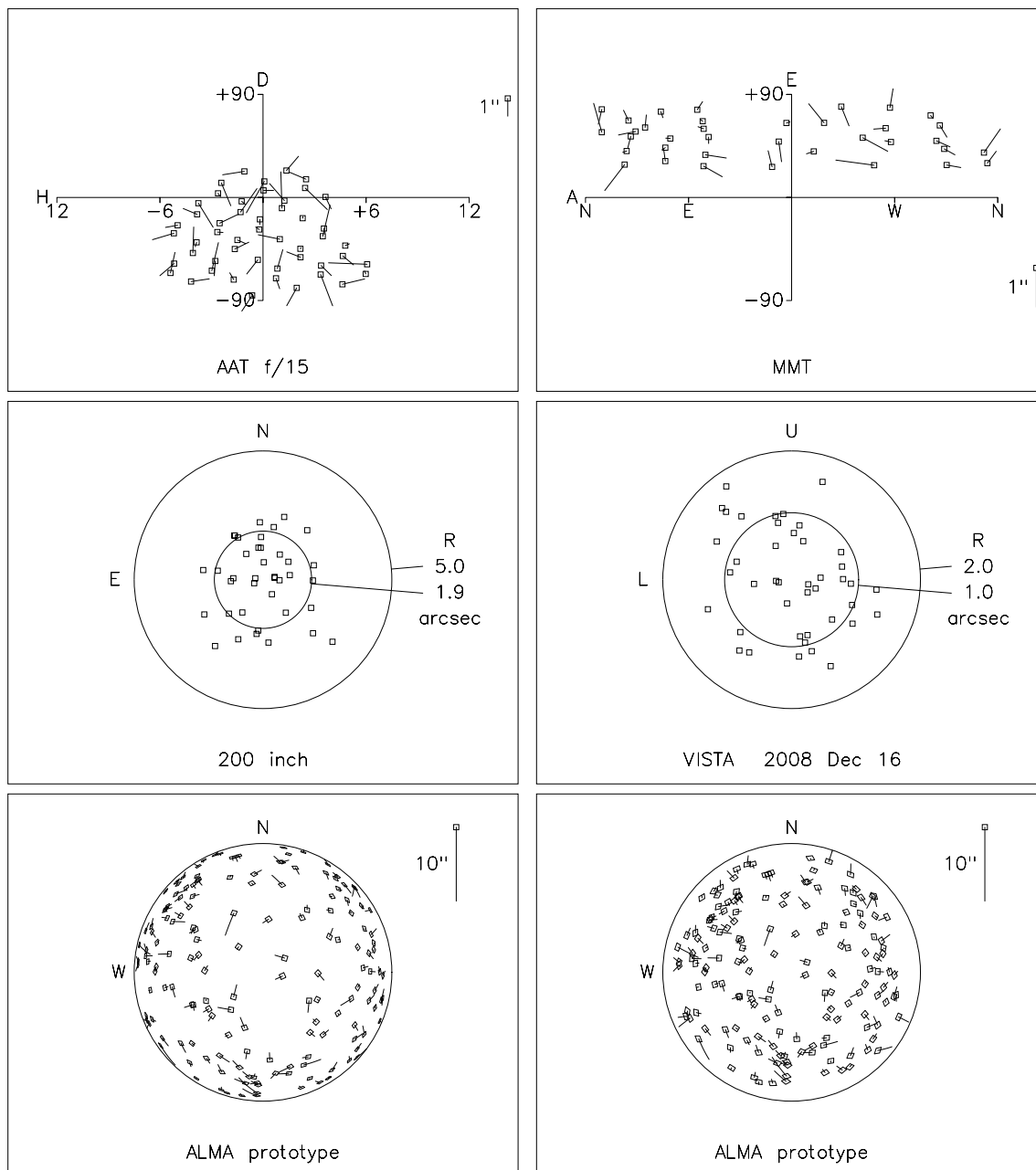
Figure 4: Example plots using the commands GMAP E (top left), GMAP A (top right), GSCAT E (center left), GSCAT A (center right), GSMAP (bottom left) and GSMAP = (bottom right).

E	in elevation (mount)
Z	in zenith distance (sky)
V	corresponding to Az/El nonperpendicularity
R	total residual

The argument *xdata* specifies what coordinate to plot against:

H	hour angle
D	declination
A	azimuth
E	elevation (mount)
Z	zenith distance (sky)
Q	parallactic angle
N	observation order

The optional argument *scale* indicates the vertical plotting scale: it is the absolute value of the largest residual to be plotted. In default, a scale is chosen automatically to suit the data.

The general strategy is to plot different components of the residuals against the various coordinates. Terms can then be added to the model (USE followed by FIT) to target any systematic effects that are seen. Some plots are more likely than others to have a mechanical interpretation, and attention should be confined to these, at least to start with. For example, an apparent relationship between polar axis elevation and azimuth, on the evidence of a G U A plot, should be treated with great skepticism (especially on an altazimuth mount), whereas systematic residuals on G N A and G W A plots (for an altazimuth) or on G U H and G L H plots (for an equatorial) are much more credible.

Because files of pointing observations are normally written in time order, G *ydata* N plots are useful for exposing shifts or drifts that have happened during the pointing run. Other x-axis meanings can be contrived by appropriately sorting the observation file prior to input.

The other plots have a variety of presentational and diagnostic roles. **GSCAT** plots residuals as a scatter diagram, like a shooting target; as well as being a good way of presenting the overall pointing performance, it exposes errant observations and abnormal distributions. **GSMAP** displays the residuals as error vectors on an azimuthal projection. There is a choice of the orthographic projection (a distant view of the celestial sphere looking down on the zenith from above) and an equal-area projection. The vectors (lines projecting from the square symbols which mark the stars) are the great-circle continuations of the pointing residuals. **GMAP** plots error vectors on a Cartesian Cylindrical projection, either HA/Dec or Az/El. **GDIST** plots histograms showing various sorts of error distribution, and is useful for testing whether the residuals are reasonably normal. **GAM** looks for changing polar/azimuth axis misalignment. Each residual is interpreted as being

due to a misalignment of the specified "roll" axis – either polar or azimuth as specified. A histogram is plotted to show if the residuals do, in fact, favor one particular direction. The mean direction is calculated and reported, and then the component of each residual in the direction of this misalignment is plotted. **GHYST** looks for hysteresis, by drawing the error vector at a position which indicates the direction from which the telescope has come, assuming that the original data file contains all the observations and in the correct order, and that any hysteresis is related to the direction of the large scale movements in cylindrical coordinates (either HA/Dec or Az/El). A numerical estimate of the hysteresis is made, by summing the residuals oriented relative to the telescope movements.

Many of the plotting commands have arguments for specifying scales and selecting HA/Dec and Az/El options etc. Full details are given in Section 7.1.

Hardcopy, in the form of a color PostScript file, can be generated by entering the command:

        GC   P   *file*

The filename defaults to `tpoint.ps` in the standard TPOINT distribution. Some experimentation with pen and background colors (see Section 8, near the end) may be necessary to get the best results, especially on black-and-white printers. Alternatively, all the pen colors can be overridden to black by instead using the command:

        GC   B   *file*

3.2   The E9 and A9 plots

When developing a pointing model it is necessary to examine the residuals in several different ways, and it is usually most convenient to use ready-made scripts in the standard procedure library to accomplish this, in particular:

        .E9   9 favorite plots for an equatorial
   or   .A9   9 favorite plots for an altazimuth

In the **equatorial** case, the nine E9 plots are as follows; Fig. 5 is an example:

TL   The east-west (i.e. $\Delta h \cos \delta$) residuals plotted against hour angle.

TC   The declination residuals plotted against declination.

TR   Zenith-distance errors against zenith distance.

CL   The east-west residuals plotted against zenith distance.
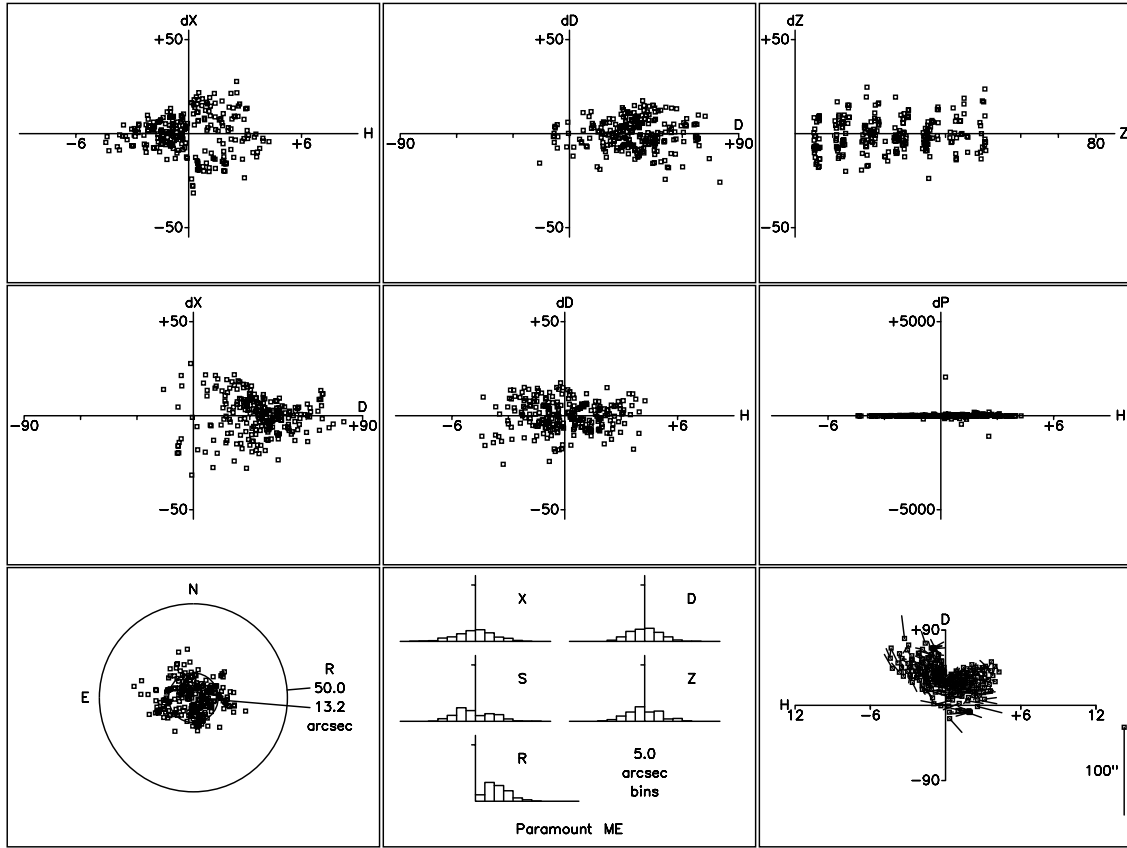
Figure 5: The nine plots produced by the command .E9

CC   The declination residuals plotted against hour angle.

CR   The residuals are interpreted as changes in the h/δ non-perpendicularity and plotted against hour angle.

BL   The "scatter" diagram, like an archery target; the inner circle shows the standard deviation of the radial error.

BC   Various histograms showing the error distributions in different coordinates.

BR   A cylindrical projection of the whole sky showing the star positions (blobs) and pointing residuals (lines).

In the **altazimuth** and generalized gimbal cases, the nine A9 plots are as follows; Fig. 6 is an example:

TL   The "left-right" (or "sideways" or "cross-elevation", i.e. $\Delta A \cos E$) residuals plotted against azimuth.

TC   The elevation residuals plotted against azimuth.
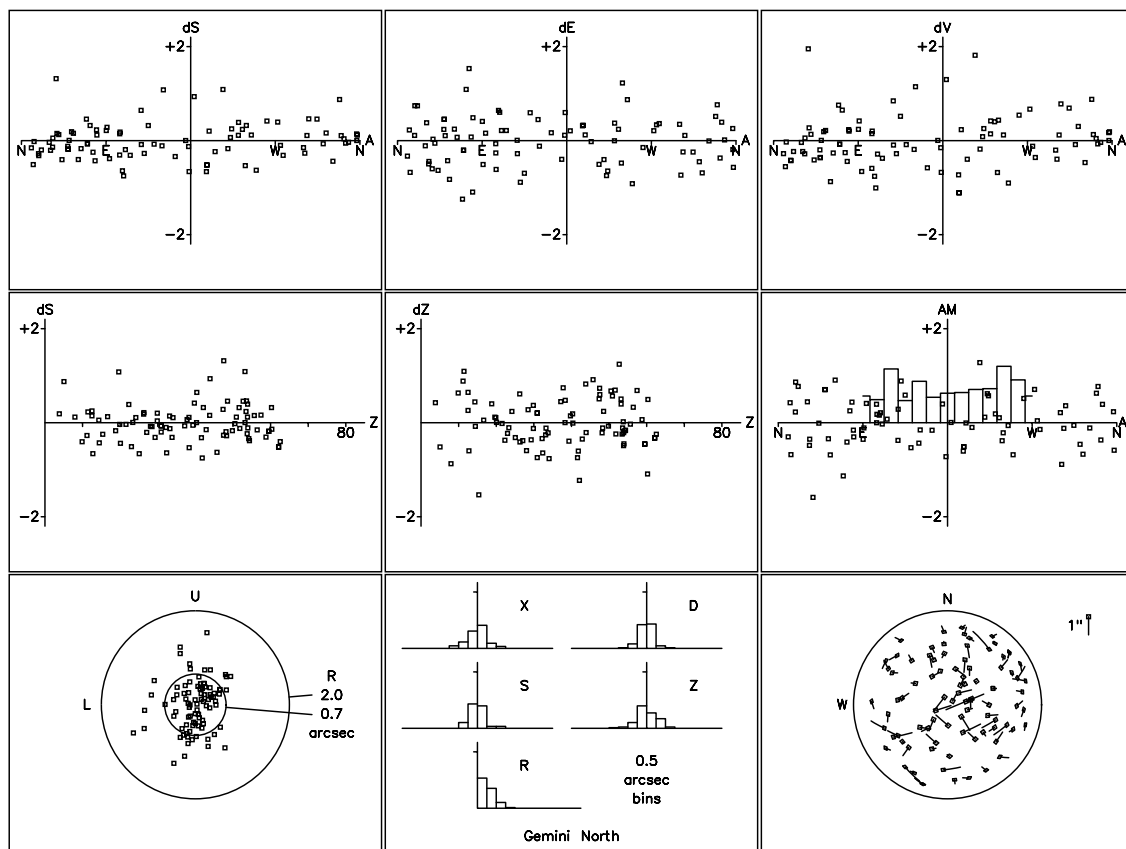
Figure 6: The nine plots produced by the command `.A9`

TR   The residuals are interpreted as changes in the az/el non-perpendicularity and plotted against azimuth.

CL   The left-right residuals plotted against zenith-distance $(90° - E)$.

CC   Zenith-distance errors against zenith distance.

CR   The residuals are interpreted as azimuth axis tilt, and plotted against azimuth; the superimposed histogram shows if the residuals are biased towards a particular tilt direction.

BL   The "scatter" diagram, like an archery target; the inner circle shows the standard deviation of the radial error.

BC   Various histograms showing the error distributions in different coordinates.

BR   An orthographic projection of the whole sky showing the star positions (blobs) and pointing residuals (lines).

4 POINTING DATA

4.1 Sky coverage and mapping order

It is important to sample the whole sky and for the observations to evenly distributed. The order in which the observations are carried out can also be significant.

Partial sky coverage means that the model must extrapolate into the unmapped areas. This is always dangerous, especially if any polynomial terms are used, because the unconstrained "end" of the region allows the correction function to diverge. Fitting across a gap, i.e. interpolating, is always safer. Sometimes limited sky coverage is unavoidable, either because of obstructions or interruption by bad weather, and in these cases the best policy is to restrict the model to terms of a harmonic character and of low spatial frequency. In fact a basic six-term geometric model plus a couple of flexure terms is relatively immune from the effects of limited sky coverage, to the extent that for an altazimuth telescope a respectable model can be obtained if only a single object is observed, sampled periodically as it tracks from rise to set.

Reasonably even distribution is important so that the model is not unduly weighted in a particular area of sky, and so that the residual plots are well-populated and unbunched. The small star catalogues that come with TPOINT meet this need. A common mistake is to observe stars on an $[h, \delta]$ or $[Az, El]$ grid. This not only biases the model to the polar or zenith region, but the residual plots become ugly and are difficult to interpret.

Order matters if the mapping run is refining the operational pointing model in real time. A degree of randomness is also useful, to expose any hysteresis and to distinguish between spatial and temporal effects.

4.1.1 German equatorials

The German equatorial mount (GEM) is a design that is often used for small telescopes, where flexibility of telescope attachment is paramount and where the need for counterweights is acceptable. Its biggest disadvantage is that observations across the meridian must be interrupted and the telescope reversed in its position relative to the tripod or pier. Because this reversal has the effect of extending the declination range into the "beyond the pole" region (see Section 4.8), there are important implications for pointing calibration that must be borne in mind when deciding the mapping strategy. This is particularly true in cases where the mount is portable, and the mapping run is refining the pointing model in real time.

A typical GEM scenario is where the detector has a limited field of view – a camera with a small chip say – and the mount's geometrical misalignments are relatively large. The first star is found, one way or another, and a "sync" is performed to reset the encoder zero

points. The problem then arises of finding a second star. Moving too far from the first star often means missing the new one altogether, so it is natural to be cautious and move only short distances at first. Gradual enlargement of the sampled area will eventually build up a sufficient data set to begin to estimate the polar axis misalignment (the ME and MA terms) and the nonperpendicularity between the telescope tube and the declination axis (the CH term). However, it is often the case that the first star following the first meridian flip will not be seen, because the sky orientation of the not-yet-accurately-known CH correction has reversed. A better mapping strategy is needed if good all-sky pointing is to be achieved early in the test, and if reliable estimates of polar axis misalignment are to be obtained speedily. The recommended procedure is as follows:

1. Find the first star, sync on it and make this the first star in the data set. Remove the pointing model or reset it to zeroes.

2. Find a second star, ideally but not necessarily some distance from the first. Execute the following commands:

   ```
   USE IH ID
   FIT
   ```

   This has the effect of establishing an "average sync" for the first two stars.

3. Find a third star, ideally but not necessarily some distance from the first two. Execute the following commands:

   ```
   USE IH ID CH
   MVET 99
   USE ID
   FIT
   ```

   After the USE command, the model comprises `IH ID CH`, and if the three stars are sufficiently spread in declination, this may allow a preliminary estimate of CH. However, the MVET command may have other ideas: the resulting model will contain the ID term at least, but IH and/or CH may be absent if MVET has decided they have not been reliably detected.

4. Find a fourth star, *this time on the opposite side of the meridian.* Be prepared to use the finder or to scan; however, this should be the last difficult star to find. Execute the following commands:

   ```
   USE IH ID CH ME MA
   MVET 99
   USE ID
   FIT
   ```

   Depending on MVET's assessment of statistical significance, the resulting model may consist of up to five terms.

5. Find a fifth star. There is no need for an additional meridian flip, and this time it should be possible to choose a star distant from the previous one. Execute the following commands (the same as last time):

```
USE IH ID CH ME MA
MVET 99
USE ID
FIT
```

Again, depending on MVET's assessment of statistical significance, the resulting model may consist of up to five terms.

6. Find a sixth star and execute the following commands:

```
USE IH ID NP CH ME MA
MVET 99
USE ID
FIT
```

By now, some indication of polar axis misalignment should be emerging.

7. As subsequent stars are acquired, it becomes feasible to look for other terms, such as TF and DAF. The MVET command will show when this stage has been reached, by removing currently ineffectual terms.

It is not necessary to stick precisely to this scheme, as long as there is a meridian flip early on, preferably before the fourth star. There will probably be two stars that are difficult to acquire, namely the first star of all and the first star after the meridian flip. These are both dealt with early on, and the improved pointing after the first few stars will speed the remainder of the test.

At the expense of a few extra minutes, it is helpful to jump around the sky during the mapping, including multiple meridian flips. This will exercise the machinery more, and help expose any hysteresis and drifts.

4.2 Making the observations

The preferred method for making the observations is to move the telescope so that the image of the specified star (or other calibration target) falls at the reference point (the nominated place in the focal plane – the center of the CCD perhaps). This is completely unambiguous and avoids various difficulties of interpretation, such as knowing which way up is north.

However, many users prefer instead – and on some telescopes there may be no choice – to take an exposure at what is hoped to be the position of the star, to measure where the image actually appeared, and from the offset to deduce the (α, δ) of the reference point. Working in this way is appealing, because it eliminates a time-consuming and delicate adjustment of the telescope, and the image analysis phase can be put off until later. However, for the method to work, it is essential to have a complete understanding

of astrometric details, in particular the image scale and the orientation of the picture. In practice this is not always the case. For example, the CCD may not be aligned accurately with declination, so that an assumed simple mapping between pixel (x, y) coordinates and sky (α, δ) is in fact not achieved. Another common blunder is to assume that an x-offset of a particular size always means the same change in the right ascension coordinate α, when in fact there is a $\cos \delta$ factor to take into account: near the pole a given x-offset will mean a bigger α change than at low declinations. And on the most precise telescopes, subtle errors may be introduced by small position-angle errors caused by the imperfect pointing model that was in service when the test was carried out.

One variant on this technique, i.e. making an exposure and recovering the pointing information later, is however completely safe. It requires the exposures to contain enough reference stars to enable a complete astrometric fit of the recorded field. The solution can then be used to predict the (α, δ) of the reference point, thereby creating what is in effect an invisible target at exactly the desired point.

Analogous remarks may be made about radio telescopes. To keep the TPOINT picture simple it is always best to "peak up" on the calibration source, using standard techniques such as fitting Gaussians to cross-scans or using the "5-point" method. However, for some radio telescopes (and some targets, such as the Sun) it may be necessary instead to make raster scans for later analysis. Doing so requires great care to be taken with sign conventions, scales and $\cos E$ factors.

4.2.1   Altazimuths and rotators

On altazimuth-mounted optical/IR telescopes there is almost always a rotatable instrument mount (or equivalently an image rotator). This introduces complications to do with the interaction between the TPOINT model and where in the rotating focal plane the target star is to be imaged, and these affect the strategy for obtaining the pointing observations. Several choices are available.

One approach is simply to fix the rotator and pretend it isn't there, so that the pointing model refers to where in the non-rotating focal plane the camera or guider etc. happens to be. But it is best to define the reference point as the rotator axis, the only place that is stationary in both the rotating and non-rotating focal planes. If, during the pointing test, the telescope is adjusted to place the stars on the rotator axis, the fitted IE and CA coefficients will be those that correspond to that spot, and this will be true whether the rotator is fixed or is allowed to rotate to maintain a specified field orientation. But if the reference point is somewhere else, say the middle of a CCD that itself is not exactly on-axis, or worse still a guide probe at the edge of the field, difficulties arise. If the rotator remains fixed during the pointing test, the resulting IE and CA coefficients will be for that spot in the non-rotating focal plane, and as soon as the rotator angle is changed the pointing will be incorrect in the rotating focal plane. On the other hand, if the rotator is active during the test, to stabilize the field, pointing terms will be introduced that depend

on the rotator angle. The usual manifestation of this is that on the GSCAT A scatter plot the points lie on a circle.

The classic solution is to center the detector on the rotator axis, which is found by taking exposures with the rotator angle moved 180°. It then should not matter whether the rotator is active or not, though it is probably best to keep the rotator stationary so that any error in the axis determination disturbs only the IE and CA coefficients and not the rest of the model.

A crude but effective alternative is to carry out the pointing test with the rotator active and to include in the pointing model the *equatorial* collimation terms ID and CH. The IE and CA coefficients in such a model automatically refer to the the rotator axis, while the ID and CH terms provide information about the displacement between the "pointing origin" (the CCD center, say) and the rotator axis. The method depends on the same field orientation being maintained throughout, and becomes inaccurate if the detector is a long way off axis – more than a few arcminutes. The ID and CH terms would normally be discarded, though if they are used in the operational pointing model they will to first order reproduce the conditions of the pointing test and make the star images fall on where the detector was rather than the rotator axis, as long as the same field orientation is used.

The most general solution is to allow the instrument rotator to be active, to record its orientation as the first *auxiliary reading,* and to include in the pointing model the terms POX and POY, the position of the pointing origin in the rotating focal plane. This is discussed in Section 5.12.

These options are summarized in the following table:

detector	*rotator*	*terms*	*remarks*
anywhere	stopped	IE CA	The IE and CA terms refer to wherever in the non-rotating focal plane the detector was placed – ideally the rotator axis.
on-axis	active	IE CA	This method relies on the rotator axis having been accurately calibrated.
slightly off-axis	active	IE CA ID CH	The same same field orientation must be maintained throughout.
anywhere	active	IE CA POX POY	The rotator angle (in degrees) must be supplied through Aux #1. IE and CA refer to the rotator axis; POX and POY may be used to calibrate the focal plane or simply discarded.

4.3   Reading and editing the observations

The TPOINT command for reading a set of pointing observations is called INDAT. Several
different formats are accepted; all are converted into a standard internal form, called the
data list. The command is:

>   INDAT *file* [*subset*] [*subset*]. . .

where *file* is the name of the file of pointing observations and *subset* (if present) associates
the observations with the specified "data subset" (see Section 5.8).

The new observations may either replace or be appended to any previous ones. This is
controlled by a flag armed by the APPEND command. The flag is reset once the new
data have been appended. In the append case the caption is reset and the one supplied
in the data file is ignored. The new latitude replaces the previous one; it would, however,
be very unusual to combine the data from several telescopes.

The MASK and UNMASK commands allow specified subsets of the observations to be
suppressed temporarily. They are useful for verifying the independence of the solution
in these different subsets. An important application is where observations from only
a specified region of the sky are included. MASK and UNMASK can also remove and
reinstate individual observations or sequences of observations. One common use of MASK
is to suppress individual outliers, observations where the total residual is so large that
something must be seriously amiss – telescope malfunction or star misidentification for
example. However, it is unwise to remove points that are just a few sigma off without
some *a priori* justification.

Possible outliers can be identified by using the SLIST command with the optional argu-
ment, the threshold radial error in arcseconds. Another clue to whether an observation is
suspect comes at the end of the FIT report where the "least typical" observation, i.e. the
one that has the largest influence on the fitted model, is identified. A more rigorous test,
but one that consumes more processing time, is performed by the OUTL command, which
not only identifies the best candidate but also reports its "badness" quantity. For normal
points, the badness should be less than unity; points whose badness exceeds a specified
value can be MASKed automatically by typing `OUTL` *v n*, where *v* is the desired cut-off
value and *n* is the maximum number of terms to MASK, defaulting to one.

Observations flagged as abnormal by either FIT or OUTL are usually plain outliers, and
immediately visible as such on a GSCAT plot, but sometimes they are wrong in a more
subtle way related to position in the sky. A quick way to check is to type `MASK` *n*, where
n is the observation number, then `MARK 2`, then `.A9` or `.E9` as appropriate to plot the
residuals: the suspect star will show up in red. (The MARKed stars can be reset to the
MASKed state by typing `UNMARK` and are then excluded from the next FIT.)

The PURGE command removes completely the MASKed observations, so that they can
be restored only by rereading the data file. Genuinely erroneous observations (for example
misidentified stars) should be removed outside TPOINT simply by using a text editor.

4.4   Different sorts of coordinates

In the internal form produced by the INDAT command, each observation consists of (i) the true direction of the star, which is known as the "observed place",[2] and (ii) the raw mechanical HA/Dec of the telescope.

The raw telescope HA/Dec normally means either the mechanical HA/Dec directly read from dials or encoders,[3] or, in the case of non-equatorial mounts, the HA/Dec obtained by applying the appropriate standard transformation to the actual readings. Az/El data, for example, are transformed by the standard text-book Az/El to HA/Dec rotation, using the longitude and geodetic latitude of the observatory.[4]

In order to avoid having to log anything which changes rapidly, the equatorial coordinates accepted by INDAT are in the form of RA/Dec rather than HA/Dec. The telescope HA is deduced simply by subtracting the given RA from the given sidereal time. This applies to all but one of the data formats, where star and telescope azimuths and elevations are supplied directly and must all correspond to one instant of time.

Starting from the star positions supplied in the INDAT file, the "observed" HA/Dec positions used by TPOINT internally are obtained by allowing as necessary for proper motion, precession, nutation, annual aberration, and light deflection, to obtain geocentric apparent place, followed by corrections for diurnal aberration and atmospheric refraction. It is also possible to supply the star data as "true" RA/Dec, by omitting the temperature, pressure, etc. in order to disable the refraction corrections. This would be done in cases where the TCS which generated the pointing data has already applied these corrections (either correctly, or at least in a way which will be consistent with any subsequent implementation of the pointing model obtained from TPOINT). In cases where the TCS neglects the small corrections for diurnal aberration, it is possible to include an optional record which disables the diurnal aberration corrections in TPOINT to match.

The modeling procedures available elsewhere in this package have the job of expressing the relationship between these two sets of coordinates. It is thus the responsibility of the TCS itself to perform accurate mean to apparent place transformations, and to allow for Earth polar motion, diurnal aberration, refraction, etc., before applying the pointing model as determined by using this package. Further information on the mean-to-observed place transformation can be found in Section 7.2.

---

[2]*Observed* is a technical term, meaning the direction of the incoming light ray, i.e. where a perfect theodolite would observe the star to be. It is a common mistake to assume that "observed" means the logged encoder readings.

[3]For a servo-controlled mount where the encoders are used to close the position loops, the correct data to log are the demands to the servos, not the encoder readings themselves. This means that any offsets or lags in the servos will automatically be taken care of in the pointing model. It also means that noise in the encoder, for example due to irregular resolution or even occasional bad readings, does not pollute the data used for the pointing analysis. Moreover, the servo demands are often much easier to obtain than the encoder readings, especially if the position servos are implemented in local processors or specialized controllers.

[4]and, for the utmost accuracy, with polar motion taken into account.

4.5   INDAT data formats

The INDAT input file consists of free-format records up to 500 characters in length, as follows:

>   CAPTION record
>   OPTION records (optional)
>   RUN PARAMETERS record
>   OBSERVATION records (plus any subset or rotator records)
>   'END' or end-of-file

Blank lines and comments (which begin with a '!' character) can be included anywhere. Long lines can be supplied piecemeal by ending partial lines with a backslash character.

The individual fields in the record descriptions below are separated by spaces. (In some cases other forms of whitespace will work, also commas.) All numeric fields are free format.

4.5.1   Caption record

The CAPTION record is simply an alphanumeric string. The first 80 characters are used; trailing blanks are eliminated.

4.5.2   Option records

There are several different OPTION records, all optional:

': NODA'	disables correction for diurnal aberration
': ALLSKY'	disables horizon/zenith/pole checks
': *equinox*'	required if telescope positions are mean places
': EQUAT'	mount is an equatorial
': ALTAZ'	mount is an altazimuth
': GIMBAL *z y x*'	mount is a generalized gimbal
': ROTTEL'	locates rotator on OTA (Cass, PF etc.)
': ROTNL'	locates rotator at Nasmyth left
': ROTNR'	locates rotator at Nasmyth right
': ROTCL'	locates rotator at coudé left
': ROTCR'	locates rotator at coudé right

The EQUAT, ALTAZ and GIMBAL options are covered in Section 5.

The correction for diurnal aberration (maximum 0''.3) should be disabled if the telescope control system itself omits it. The ALLSKY option is useful in cases where, for one reason or another, the observations exceed the normal zenith distance range. Where the telescope positions are mean places, only one *equinox* (probably 'B1950' or 'J2000') may be specified, and applies to the whole file.

The rotator locator options, ROT... are used when the pointing origin (e.g. a guide probe) is on a rotating instrument mount and is not on-axis. They can also appear later in the file, allowing such observations made at different foci to be mixed. See Section 5.12.

4.5.3 Run parameters record

The RUN PARAMETERS record is a single line of text containing the following:

> latitude (°,′,″)
> UTC date (y,m,d)
> temperature (°C)
> pressure (mB = hPa)
> height above sea level (meter, default determined from pressure)
> relative humidity (range 0–1, default 0.5)
> observing wavelength (micrometer, default 0.55)
> tropospheric lapse rate (°K/meter, default 0.0065)

Which of these parameters are needed depends on the chosen observation record format (see below). The latitude is mandatory, and the only one used in the case of Format 4, where the observation consists of simply the star and telescope Az/Els. If the UTC date is omitted, the star and telescope data must not be mean places. If the refraction data (temperature and so on) are omitted, no corrections for refraction are made. If either the pressure or the height is omitted, it is estimated from the other.

Optical refraction is computed for wavelengths below 100 micrometers, and radio refraction for wavelengths longer than this figure. In the radio case, it is important to specify the humidity accurately.

Note that the pressure is actual pressure at the site (QFE), not the equivalent sea-level pressure (QNH). For a site at sea level it will be around 1000 hPa (millibars); for a high altitude site it will be a much lower figure.

4.5.4 Observation records

Each OBSERVATION record is a single line of text corresponding to one star observed; there is a choice of four formats:

> Observation record Format 1:

star geocentric apparent RA/Dec (h,m,s,°,′,″)
telescope raw RA/Dec (h,m,s,°,′,″)
local apparent sidereal time (h,m)
[up to 2 auxiliary readings]

Observation record Format 2:

star mean RA/Dec (h,m,s,°,′,″, μ_α,μ_δ,equinox)
telescope raw RA/Dec (h,m,s,°,′,″)
local apparent sidereal time (h,m)
[up to 2 auxiliary readings]

Observation record Format 3:

'*'
identifier from star catalog
telescope raw RA/Dec (h,m,s,°,′,″)
local apparent sidereal time (h,m)
[up to 2 auxiliary readings]

Observation record Format 4:

star "observed" Az/El (°,°) – the true direction
telescope raw Az/El (°,°) – where the mount was commanded to point
[up to 2 auxiliary readings]

Notes:

- Although star positions in Format 1 are usually apparent right ascension and dec-
  lination, together with local apparent sidereal time (LAST), it is equally valid to
  provide instead celestial intermediate reference system (CIRS) right ascension and
  declination, together with Earth rotation angle (ERA). The LAST or ERA is used
  only to transform the supplied right ascensions to hour angles; indeed, it may be
  more convenient to supply hour angles directly and to set LAST/ERA to zero.

- Using Format 4 requires precise times to be extracted from the telescope control
  system in order to predict the exact Az/El of the star, whereas Formats 1-3 use
  instead the telescope RA/Dec, which is unlikely to vary rapidly during tracking of
  a star and is therefore easier to get right. Moreover, precisely consistent Az/El and
  time information may simply be unavailable if special provision has not been made

in the control software.[5] However, in the case of Formats 1-3, if sidereal time of high precision is available, this information can, and should, be supplied, by appending decimals to the sidereal time minutes.

- In Format 2, the units for μ_α and μ_δ are, respectively, seconds and arcseconds per Julian year. (Parallax is neglected.) Note that in Format 2, although the star positions are mean place the telescope positions are still "raw", not a mean-place representation.

- In Format 2, the equinox is likely to be J2000 and the star data ICRS rather than being referred to a dynamical system as in the past. The astrometric algorithms used by TPOINT in fact always apply the small ($\sim 23\,\mathrm{mas}$) offset between ICRS and mean J2000, and so by specifying equinox J2000 the star coordinates are interpreted as ICRS positions.

- Following the normal convention, the azimuths in Format 4 are reckoned from north through east (though internally within the TPOINT software they go from south through east).

- In the "generalized gimbal" case, both the star and the telescope $[\,Az, El\,]$ are indeed $[\,Az, El\,]$, not raw mount coordinates. In other words, the telescope measurements must be converted from their raw form into their $[\,Az, El\,]$ equivalents. In "beyond the pole" cases, appropriate changes must be made to ensure that the recorded $[\,Az, El\,]$ reflects the condition.

- Each format permits up to two auxiliary readings to follow the mandatory fields for the given record format. If more than two are required, they can be included by placing an ampersand character $'$&$'$ between the mandatory fields and the auxiliary readings. The maximum number of auxiliary readings is 99.

- If auxiliary readings are not supplied, a sequence number and its square are inserted into the first two. The sequence number is the number of the observation record divided by 100. The feature is useful for fitting terms that are time dependent, as for evenly-spaced observations the stored number is a surrogate for time.

- If a mount type has not already been specified, through an appropriate option record, the first "beyond the pole" observation in Formats 1, 2 or 3, or "beyond the zenith" observation in Format 4 will summarily impose a selection of EQUAT or ALTAZ.

---

[5] A word of advice: do not take the line of least resistance and supply star positions that contain the corrections applied by the current operational model. It is very tempting to do this, because all that needs to be logged is where the telescope was told to point and the small adjustments that proved necessary to achieve final alignment. The disadvantage of this approach is that the resulting TPOINT model is *in addition to* rather than *instead of* the current operational model. If, at a later date, it is necessary to go back and re-analyze old data, only if meticulous records have been kept of what model was in use for each test will re-analysis be possible. In practice this doesn't happen. There is really only one right way to do it: the telescope control software must be able to log the true star direction and the raw telescope demands while at the same time implementing an operational pointing model (without which acquisition of the calibration stars would be at best slow, at worst impossible).

4.5.5   Subset records

Individual observations may be flagged as members of "data subsets", with access to their own pointing terms. Full details are given in Section 5.8. Subset membership is controlled through "D-records", interspersed with the observation records. The following options are available:

D/*subset*	subsequent observations in specified subset only
D *subset*	subsequent observations in specified subset only
D+*subset*	subsequent observations in specified subset also
D−*subset*	subsequent observations not in specified subset
D−	subsequent observations not in last-mentioned subset
D	subsequent observations not subsetted
D/	subsequent observations not subsetted
D+	subsequent observations in last-mentioned subset also

D-records override any subset name(s) specified on the INDAT command.

4.6   Non-standard data formats

Two approaches are available for reading "foreign" data formats. The first is to implement a local TPOINT command which accepts the foreign format and converts it directly into the internal form. The second approach, which does not involve modifications to TPOINT, is to write a freestanding program which translates the foreign format into one of the INDAT formats. Such translation programs can be tricky to write, and frequently involve applying positional astronomy adjustments that will all be undone again when INDAT reads the file. Nevertheless, this approach is probably the best in most cases.

4.7   Star catalogs

Several small star catalogs are supplied with the TPOINT system, as follows:

stars20b.dat	102 FK5 stars, 5^m and brighter, 20° spacing.
stars20f.dat	102 Tycho-2 stars, 7.0^m-7.5^m, 20° spacing.
stars15.dat	182 Tycho-2 stars, 7.0^m-7.5^m, 15° spacing.
stars10.dat	411 Tycho-2 stars, 7.0^m-7.5^m, 10° spacing.
starssch.dat	UK Schmidt calibrators
stars.dat	default

`stars.dat` is loaded automatically when the system is initialized. TPOINT is delivered with `stars.dat` containing a concatenation of `stars20b.dat` and `starssch.dat`.

The catalogs are needed for cases where, in a file of pointing observations, the stars' catalog numbers are given rather than their full $[\alpha, \delta]$, proper motions etc. However, they are also valuable for actually carrying out pointing tests; using the chosen catalog and observing every star visible on the night concerned, a set of observations will be obtained where the samples are evenly spread over the sky, and where the plots of the results display minimal "bunching." Regarding the latter effect, it is a common mistake to select stars on a straightforward $[\alpha, \delta]$ grid; because the stars all lie on meridians or small circles, they are bunched together on the equatorial plots, making it harder to see trends.

A private star catalog can be substituted, either at startup time via the command line or during a TPOINT session via the INST command. The original catalog can be restored at any time by means of an INST command with no arguments.

A star catalog is a sequential file of up to 180-character records. Here is an example record:

```
072852   10 02 54.793   -04 43 52.01   +0.0042 -0.103   2000.0
```

The first field of each record is an alphanumeric star identifier. The remainder of the record is the mean RA/Dec (hours, minutes, seconds, degrees, arcminutes, arcseconds), RA/Dec proper motions (seconds and arcseconds per year) and equinox (optionally preceded by 'B' or 'J' to distinguish between the FK4 and FK5 systems[6]). Two optional fields may be appended, respectively the parallax in arcseconds and the radial velocity in km/s (+ = receding), though only in extremely rare cases will this affect the pointing analysis perceptibly. The equinox field may be omitted and defaults to J2000/ICRS. Free-format input decoding is used. The file is terminated by 'END' or end-of-file.

The standard TPOINT syntax rules apply to such catalog files, which may thus contain blank lines and comments (beginning with '!') to enhance readability.

n.b. The star identifier is not case-dependent unless enclosed by quotes (double or single). However, spaces are not allowed even if quotes are used.

4.8   Coordinate ranges, and "beyond the pole"

Most equatorial mountings can be configured so that the mechanical declination range extends "beyond the pole". The simple and obvious case is a horseshoe or fork mounting that allows access to regions of sky underneath the pole, where circumpolar sources pass

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[6]TPOINT neglects the tiny distinctions between J2000/FK5/ICRF.

through lower culmination. Less obvious, but a fruitful source of confusion, is what happens with asymmetric mounts: cross-axis or, in particular German equatorials. In this case, in order to cross the meridian the telescope has to pass through the pole to the declination range beyond, while HA is offset by 12^h.

TPOINT accepts data containing a mixture of observations, and fits models where the various pointing terms change appropriately as the telescope switches into the other configuration. To obtain this behavior, telescope $[\alpha, \delta]$ coordinates in the INDAT data file must be "mechanical" rather than "celestial". This means that in one of the two configurations, declinations beyond the pole should appear (for example $+123°$ at a northern-hemisphere site, $-99°$ at a southern-hemisphere site) paired with hour angles that are 12^h from the celestial value. Such observations are flagged 'b' on the SLIST and FLIST output; the $[h, \delta]$ coordinates reported appear in the conventional ranges.

It is usual for mount controllers on amateur telescopes to work entirely in celestial coordinates, and not uncommon for the vital "beyond the pole" (also known as "side of pier") state to be invisible to TPOINT. The symptoms of this problem are (i) all logged telescope positions have δ in the normal range (i.e. none where $|\delta| > 90°$), (ii) TPOINT reports a very poor RMS result, (iii) the dX $(= \Delta h \cos \delta)$ versus h residuals have a discontinuity on the meridian, and (iv) the operational pointing is poor, and may differ markedly on the two sides of the meridian. When this happens, the workaround is to fit separate models for the two sides of the meridian and have the TCS switch between them when the meridian flip maneuver is carried out.

Note that the "rigorous fitting" method (Section 5.10), where the mount type is explicitly specified, is mandatory for coordinates outside the standard range. This can be enabled either by an appropriate choice of option record in the INDAT file or will be automatically invoked when the first beyond the pole/zenith observation is encountered.

Implementation of a pointing model should include provision for detecting the "beyond the pole" case; in general, the mechanical coordinates should be used in the formulas, and the corrections applied to the mechanical coordinates before the latter are transformed back into celestial ones.

Analogous remarks apply to altazimuth mounts and generalized gimbal mounts. Note however that it is a very bad idea to take an altazimuth through the zenith, as any slightly loose mechanical and optical components will slump into a different state and cause pointing errors.

4.9   Sample data

Four examples of authentic pointing data are provided: from the UK Schmidt Telescope (1.2 meter aperture, fork equatorial); from the Anglo-Australian Telescope (3.9 meter, horseshoe equatorial) in the f/15 Cassegrain configuration; from the Palomar 5 meter telescope (horseshoe equatorial) in the f/17 IR configuration; and from the central reference

telescope of the pre-upgrade Multiple Mirror Telescope (4.5 meter equivalent aperture, altazimuth). The UKST file refers to the star catalog `starssch.dat` (the same stars are included in the default `stars.dat` file; the other three files use explicit star positions and are therefore self-contained). The filenames are as follows:

UK Schmidt	`ukst.dat`
AAT	`aat15.dat`
Palomar	`hale.dat`
MMT	`mmt.dat`

(When using the INDAT command it is not necessary to specify the `.dat` filename extension. If the filename doesn't contain a period you can append a forward slash `'/'` to stop the `'.dat'` being added.)

The recommended analysis procedure, which was described in Section 1.6, earlier, begins as follows:

```
    INDAT file
    CALL EQUAT                          (equatorial)
or  CALL ALTAZ                          (altazimuth)
    FIT
    CALL E9                             (equatorial)
or  CALL A9                             (altazimuth)
```

It is then usual to start trying obvious extra terms via the USE command – tube flexure TF, fork flexure FO, etc., as appropriate. The credibility of the added terms can be judged partly by the significance of the fitted coefficient (the ratio of the coefficient value to its σ estimate) and partly by its influence on the population standard deviation for the fit as a whole. New terms should have at least a 2σ significance, and should reduce the PSD. Another guide is the MVET command, which ranks the model terms in decreasing order of credibility and suggests which terms may be doing more harm than good.

Example models (which in the case of the UKST and AAT are the ones actually in service) are supplied as procedures, yielding the results shown in the following table:

datafile	procedure	$\sigma/''$	terms
UKST	UKST	6.17	7
AAT15	AAT	1.26	10 fitted + 4 fixed
HALE	HALE	2.23	11
MMT	MMT	0.55	13

To reproduce, for example, the AAT result, you would simply type:
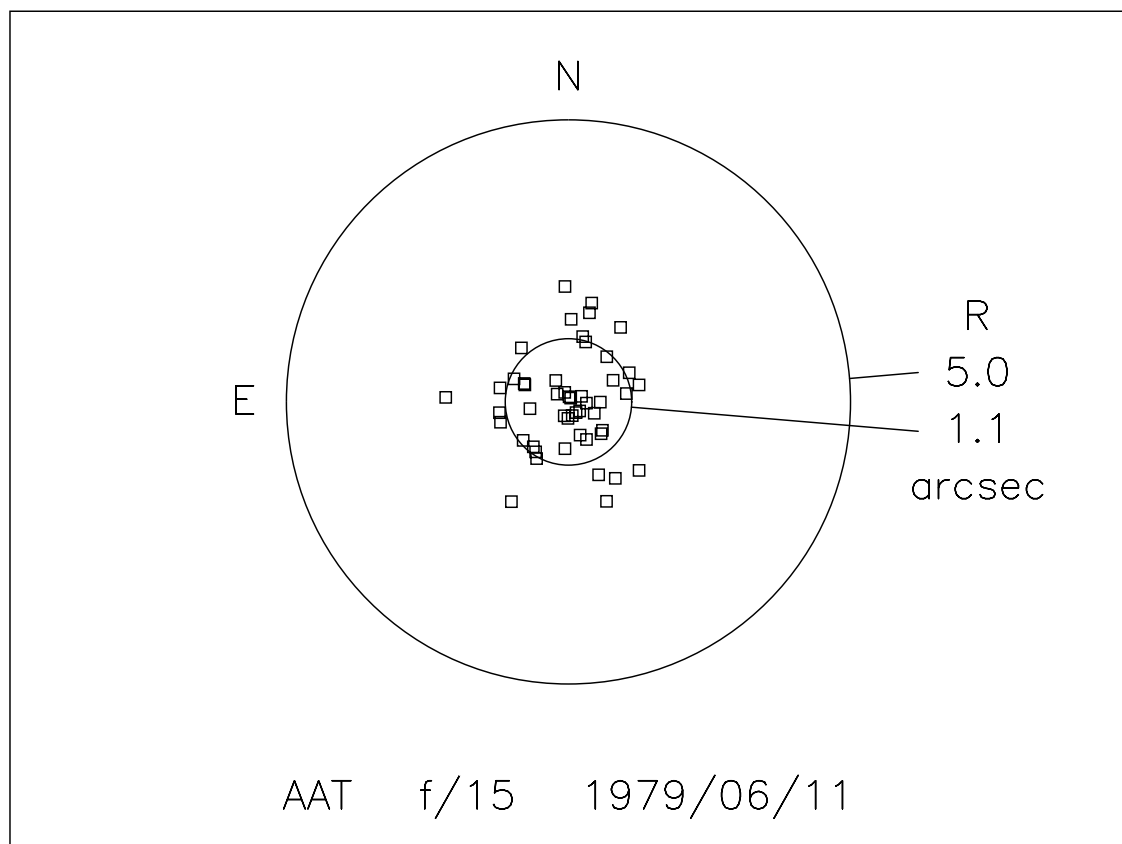
Figure 7: Anglo-Australian Telescope, f/15 focus, after fitting the TPOINT model.

```
        INDAT aat15
        CALL AAT
```

To display this AAT result as a scatter diagram, type:

```
        GSCAT
```

The resulting graphic is illustrated in Fig. 7. The circle in the middle of the diagram is roughly the size of a dime seen from a distance of one mile (or a Euro at 2 km).

4.10   Simulated pointing tests

When developing the pointing-model part of a telescope control system, refer to *The Pointing Terms in Detail,* later, for information on the mathematical form of TPOINT's various pointing terms. The operational implementation of the terms may well involve techniques which differ in some way from TPOINT's – perhaps by being more elaborate and general. Any substantial inconsistencies between TPOINT and the telescope software

will manifest themselves as pointing errors, and telescope users will not experience the levels of performance which the TPOINT results appear to offer.

In order to check that the model as implemented in the telescope system is consistent with TPOINT, a "dummy" pointing test is recommended. This is like a real pointing test except that the telescope is left where it is after each blind setting rather than being guided onto the star. When the dummy pointing test is reduced with TPOINT, a perfect fit should be reported, and the coefficients should exactly match the values used by the control software. Without a test of this sort, errors of scaling and (especially) sign may go unnoticed.

Note that the dummy pointing test just described is a check on the software alone, with the telescope itself playing no part. Consequently, it is usually best to arrange that the control software can operate in a "simulation" mode, capable of generating a dummy pointing test offline. It is **strongly** recommended that dummy pointing tests be carried out from time to time, to verify that any revisions of the telescope software and TPOINT have not led to incompatibilities.

When TPOINT is used to process data from dummy pointing tests, it should be borne in mind that only if the model is implemented in *exactly* the same way is it is in TPOINT will the residuals be identically zero. For example, if spherical trigonometry formulas are used to apply corrections for which TPOINT uses a vector formulation, this may have detectable effects, especially if the affected terms have large coefficients and particularly for stars near the pole and/or zenith. Another possible cause for slightly imperfect fits is where all the terms in the model are "parallel" rather than "chained"; although TPOINT computes all the corrections from the same starting-point, it accumulates them sequentially, and the telescope-control code should follow suit. Grouping the terms sensibly and then chaining the groups will, in general, give better results, especially if any of the coefficients (for example encoder zero-points) are large. Even better results are achievable by using the "rigorous fitting" option (Section 5.10), with matching telescope control software. This is described later.

5   ADVANCED TECHNIQUES

TPOINT allows a straightforward model for a reasonably well-behaved equatorial or altazimuth telescope to be generated easily and without great cunning or insight. It also provides the tools more experienced and determined users will need when conducting especially searching analyses and tackling difficult cases.

5.1   Building models

As already described, the general strategy for modeling a telescope from scratch is to input a data file with INDAT, to set up a basic geometrical model using CALL EQUAT or CALL ALTAZ, and to fit using the FIT command, repeating as necessary until the coefficients settle down. With the aid of the G... commands, plots of residuals can then be made and inspected for signs of systematic error. Plausible flexure terms can be tried (USE TF etc.), and any others that the particular telescope design suggests.

TPOINT provides expert help with modeling, in the form of the FAUTO command and the .EFIT and .AFIT procedures. In many cases, after the observations have been input using INDAT, all that is needed is the command:

```
FAUTO
```

Quite good results are usually obtained, and the resulting model can form the basis for further fine-tuning by hand. A similar strategy to that used by FAUTO is employed by the library procedures .EFIT (for an equatorial) or .AFIT (for an altazimuth). Unlike FAUTO, which automatically reverts to simpler models when the number of observations is limited, these procedures will always attempt an exhaustive analysis, which can be informative. Moreover, the supplied scripts form a good template for further experimentation, perhaps tailored to a particular telescope or antenna. The scripts search for statistically meaningful terms up to 8th harmonic; the FAUTO command accepts an optional argument that allows the highest harmonic to be specified.

When adding new terms, pay attention to the standard deviation of the new coefficient, the effect on other terms, and whether the population standard deviation has gone down; a new term will almost always reduce the RMS but the PSD is a better indication of whether the improvement is real.[7] An impersonal assessment of the credibility of the individual terms is made by the command MVET. This performs a series of fits with the term temporarily omitted, to see if there is significant degradation. Ineffectual terms are

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[7]You can reassure yourself that PSD is the more honest figure by using the command SAMSIG. This makes an independent estimate of the PSD by carrying out a separate fit for every observation, with that observation excluded ("jackknifing"). In most cases the agreement is extremely close, within a couple of percent.

flagged; if the command is followed by the optional argument ′n′ the worst n of these (if any) are automatically removed.

If you try to use two terms which are more or less indistinguishable (for example CH and PXH0, which are identical), the condition will be reported; if this happens, get rid of one of them via the LOSE command. In such ill-conditioned cases, the singular value decomposition (SVD) methods used by FIT will normally return a workable model, with the "true" value of a duplicated term being partitioned between the two (or more) coefficients involved. Two common cases are (i) if two inseparable terms are present from the start, they each receive an equal share of the value, and (ii) where a new term is added to an already fitted model, and that term is inadequately distinguished from something already present, then the new term will be left close to zero. This behavior can be controlled by means of the FITTOL command, which allows the SVD ill-conditioned criterion to be set. A command FITTOL 0 will switch off the detection of ill-conditioning, whereupon FIT will return a conventional least squares fit, and any highly correlated terms will head off towards cancelling infinities. A FITTOL argument of between 10^{-3} and 10^{-2} will give a useful degree of control over ill-conditioning; the value is set to 10^{-3} initially. With FITTOL arguments much bigger than 10^{-2}, there is increasing danger that respectable terms will be excluded from full fitting. However, whenever FIT decides to take action over ill-conditioning, it reports that this has occurred.

Do not try to extract more information from a given sample of data than the size of the sample justifies. A preliminary assessment of a telescope's capabilities can be made using perhaps 20-30 stars. Routine fitting of a typical operational telescope model, consisting of six geometrical terms, two or three flexures, and perhaps a few scale adjustments, centering corrections, etc., calls for 50-100 stars, well-distributed over the whole observable sky (see Section 4.1). A campaign to expose high-frequency flexures and bumps should not be embarked upon without a sample of 500-1500 stars, obtained by combining multiple tests by means of the APPEND command and the "data subsets" feature (see Section 5.8).

5.2   Exposing unmodeled effects

When first analysing a new telescope, it is not uncommon to see obvious systematic (i.e. visibly non-random) residuals on the simple graphs of error in one coordinate plotted against that or another one – plotting error in zenith distance against zenith distance (G Z Z) for example. However, once these straightforward effects have been treated, systematic errors can still hide in what looks like noise. Some of these can be exposed by using more specialized plots – zenith distance errors against parallactic angle (G Z Q), errors in HA/Dec nonperpendicularity plotted against HA (G P H), and so on. However, certain effects which depend simultaneously on two coordinates may prove more stubborn; given a data set of adequate size, the solution is to use the MASK and UNMASK commands to select bands in one coordinate, allowing the residuals for that one band to be plotted.

At various stages, the GHYST command should be tried, to assess whether the current pointing accuracy seems to be limited by hysteresis.

Do not overlook the option of plotting residuals against observation number (G x N). As long as the original data file contained the observations in the order in which they were made, such a plot will expose effects which are varying with time. For example if an encoder has suddenly jumped by some amount, a not uncommon fault due either to electronic malfunction or operator error, this will be very apparent from the appropriate G x N plot. Drifts due to temperature changes can also be revealed using such plots. All the other graphs will have shuffled the data and any glitch or drift will not, as a rule, be visible.

5.3   Physical *versus* empirical

When pursuing low-level flexures and irregularities, difficult questions arise. To what extent is the model physically meaningful? Has adding empirical terms affected the supposedly well-understood underlying model? Is it worth trying to keep a grip on physical reality, or wouldn't it be just as good to fit a massive set of polynomials or harmonics?

An approach that seems to preserve the considerable advantages of having a model firmly based on mechanical reality, yet which allows all the power of empirical modeling to be unleashed, is to construct a model which includes both physical and empirical terms, but at no stage to leave both sets free to float at once during fitting.

5.4   Command scripts

Advanced modeling will require repeated application of complex and subtle actions. This will take time and be prone to mistakes. A good way to proceed is to pre-program the key steps using a private procedure library. Such a library can be edited during the TPOINT run in another window (or by means of the SPAWN command) and then re-input with the INPRO command. A private library is also an option when running in batch mode; instead of specifying TPOINT commands in the batch control file, the latter can simply start TPOINT, read the procedure library with INPRO, and execute the required library routine by means of an appropriate CALL.

When constructing a private library, it is a good plan to start with the standard library `procs.dat` as the procedures it contains may be useful as templates. However, it is possible (and commonplace) for a private library to contain a mere handful of procedures, possibly just one.

5.5 The UNFIT command

It is sometimes necessary to express the pointing residuals in the context of a model that differs from that in effect when the data were obtained. This can be accomplished using the UNFIT command.

UNFIT applies a pointing model in reverse, taking the current adjusted positions and predicting the observations that produce those adjusted positions when the model is applied. Thus an adopted standard model can be applied to a set of pointing residuals to yield new "observations" which can be combined for further analysis. Two modes of operation are provided:

	UNFIT	to apply the current model
or	UNFIT N	to apply a null model (coeffs all zero)
or	UNFIT Z	to reset the residuals to zero

If the star-to-telescope modeling option has been chosen (via the ADJUST command), the star positions are set and the telescope positions left alone. If the telescope-to-star option has been chosen, the reverse is true.

To understand UNFIT, think first of what the FIT command does. Assume that the telescope-to-star modeling option has been chosen (the default). Under these circumstances, the FIT command takes the raw telescope positions and computes what coefficient values in the current model will give the smallest residuals, then applies the model to the "raw telescope" positions to give the "adjusted telescope" positions. The differences between these "adjusted telescope" positions and the "star observed" positions are the pointing residuals. UNFIT leaves these pointing residuals at their current values, but applies the pointing model in reverse to generate fictitious "observations" (in this case raw telescope positions) which are consistent with both the current model and the current residuals.

If the current residuals and coefficient values are both simply the result of fitting, UNFIT will not have any significant effect. However, if one or more of the coefficients is set to a different value, UNFIT will produce a changed set of observations which, if fitted with the same model, will reproduce the changed coefficient values. This is how data from different runs can be combined – as will be seen in Section 5.7.

Very often, a null model (all coefficients zero) is required, and here the UNFIT N command is useful. UNFIT N has essentially the same effect as setting all the coefficients to zero by hand and then executing an UNFIT command, except that it leaves the original coefficient values intact. UNFIT N is useful for recording pure residuals and eliminating the need for fitting with the original model when new terms are being investigated.

The remaining mode, UNFIT Z, produces a result that is consistent with the current coefficient values and zero residuals. One use is investigating any consequences to model-fitting of the particular sky distribution of the current set of observations.

5.6   Reducing multiple data sets

Observations made at different times cannot necessarily be reduced using a single pointing model. The optical configurations may be different, and there can be small drifts and changes in zero points caused by temperature variations or mechanical variations. (By the same token, it is likely that some sort of *ad hoc* change to the model will be required in the operational case in order to find the first star.) When the modeling possibilities of any one set of observations have been exhausted it will be necessary to combine the results of several runs if further systematic effects are to emerge from the noise.

There are two ways of accomplishing this: by using UNFIT (Section 5.7) and by means of *data subsets* (Section 5.8). The two methods will give the same end results; the former avoids simultaneous fitting of very large data sets and models, while the latter, which is preferable, is more direct and does not require iteration.

5.7   Combining data with UNFIT and OUTDAT

One way to combine data acquired on different occasions is to normalize each run to a standard state before combination and fitting. The procedure is as follows:

1. Fit all the data to a model that comprises a fixed "core" and a variable "specific to run" portion.

2. In each case, set the fitted model terms to standard values (typically zeroes) and perform an UNFIT followed by OUTDAT to a series of scratch files.

3. Concatenate the resulting data sets using INDAT and APPEND.

4. Fit the entire model, including the "core" terms. Those terms that were allowed to vary in the previous fits should stick at close to their standard values (e.g. zeroes).

5. Fix the core terms and repeat from Step 1.

6. Continue until no further improvement occurs.

Within a few iterations, the core terms will have stabilized and the analysis is complete. The operational model will consist of these core terms plus other terms that can be recalibrated on a regular basis, using a relatively small number of observations.

5.8   Using data subsets

A more direct method of dealing with heterogeneous data, that leaves the original observations intact throughout the modeling process, is to use *data subsets.* This is one of TPOINT's most powerful capabilities. Its principles are as follows:

- A data subset is identified by a user-specified string.

- Any observation is a member of zero or more data subsets.

- A pointing correction term can be linked to a specified subset when the USE command adds it to the model; there can be multiple instances of the same correction term, each applying to a specified subset, and the model can contain a mixture of normal (i.e. "global" terms) and subsetted terms.

- The FIT command accepts simultaneously fits all the terms in the model, matching subsetted terms and observations appropriately.

A typical application of the technique would be when combining several runs that share a common flexure model but have different encoder zero points or misalignment terms, or where something has changed abruptly during the run. A particularly common case is an equatorially mounted telescope without absolute encoders, where in preparing for an observing session it is usual to "sync" on a bright star. This has the effect of introducing index corrections IH and ID that are different for each session. The fitting procedure would be:

1. Use INDAT and APPEND to produce a concatenated data file, placing each set of records in subsets `A`, `B`, `C` etc.

2. With the USE command, create this model:
      IH/A ID/A IH/B ID/B IH/C ID/C ... TF NP CH ME MA

3. Execute a FIT command.

The fit will produce a single set of core coefficients (`TF NP CH ME MA`) but multiple independent index errors (`IH/A ID/A IH/B ID/B IH/C ID/C`...). The latter can be discarded, leaving the fixed "core" model in service, to be supplemented by the start-of-session sync.

There are certain restrictions on subset names. They must not contain spaces or other blanks, nor '!', nor start with '*' or '='. They are case-independent, and appear on reports in uppercase.

5.8.1   Controlling subset membership – INDAT and SUBSET

The INDAT command provides two methods for controlling subset membership of the observations in the file it reads. The first method is to append one or more optional arguments to the INDAT command:

> `INDAT` *file subset subset...*

where *file* is the name of the file of pointing observations and *subset* the name of a data subset to which the observations will belong. The alternative is to embed within the data file "D-records" – see Section 4.5.5.

The subset membership of individual observations can be controlled during data analysis by means of the SUBSET command. This works in conjunction with the MASK and UNMASK commands, that can be used to select specific records or ranges of records. Once the required observations have been so identified, the command:

> `SUBSET /` *subset*

will cause each observation that is currently in the MASKed state to become members of the specified data subset. If the argument is omitted, the observation(s) lose all subset memberships.

Once the SUBSET command has been applied, the selected observations can be brought into use with the UNMASK commend.

5.8.2   Model terms for data subsets – USE, LOSE, FIX, CHAIN and PARAL

Selected pointing terms can, as appropriate, be brought to bear on specified data subsets by appending a forward slash and the subset name to the term name. The resulting ensemble, for example `'CA/060401'`, becomes in all respects just like a modeling term of that name, in particular when using the USE, LOSE etc. commands.

For example, typing `'NPAE CA/A CA/B AN AW'` would identify five terms: a CA term applying to observation subset A, another CA term but instead applying to observation subset B, and NPAE, AN and AW terms applying globally.

To reduce the amount of typing, limited defaulting and wildcarding is supported:

term	term that applies to all observations
term/`=`	term that applies to the latest subset
term/*subset*	term that applies to specified subset

*term/***	all current terms of specified name
*	all current terms of whatever subset
*/=	all current terms of latest subset
*/*subset*	all current terms of specified subset
/*subset term1 term2...*	multiple terms that apply to the specified subset

The "latest subset" is that of the previous term in the current command line. It is initially the empty string and becomes empty again if a global term is specified; otherwise it is the last subset to be specified. For example, typing `'USE IH/RUN3 ID/= CH/='` would be the same as typing `'USE IH/RUN3 ID/RUN3 CH/RUN3'`.

5.9   Order of terms

To match different styles of telescope control system, the model can either start with raw telescope positions and predict the corresponding observed[8] place, or alternatively can start with observed place and predict the required raw telescope position. The selection is made with the ADJUST command. The sign convention for the coefficients is the same for both options, so that the two options should deliver coefficients that are substantially the same. When the ADJUST command is used to change the option, the order of the terms in the model is reversed so that more or less the same coefficient values will be produced if a FIT is carried out (following a RESET to cancel the previous set of corrections).

Normally, each term in the model is *chained* to the previous one, the input position for each term being the output position from the previous term. Sometimes this may not be appropriate, and a set of terms can instead share one input position and their adjustments be added in as a group; in this case the terms are said to be *parallel*. The commands CHAIN and PARAL select which option applies to a given term, the first in a parallel group being marked "chained" and the rest marked "parallel" to indicate they share the former's starting point.

In typical cases the coefficients will not be much altered by changing the order of terms, or switching terms between chained and parallel. Significant changes are likely only if some coefficients are large, or if high order polynomials or harmonics are employed. It is nevertheless reassuring if the model being fitted matches the way the pointing corrections are implemented in the telescope control system itself, in direction, order, formulation, and chaining. The purest match is achieved with the "rigorous fitting" option, which is about to be described, and compatible control software.

A plausible ordering and choice of chained/parallel can be applied to the current model by using the command MODOR.

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[8]As already pointed out in Section 4.4, "observed" has the specific technical meaning of the true line-of-sight direction, and hence is the predicted position of the star taking into account everything up to and including diurnal aberration and refraction.

5.10   Rigorous fitting

TPOINT models are most simply viewed as a series of more or less independent terms. During fitting, each term is treated separately, apart from the input to a given term being slightly affected, in the "chained" case, by its predecessor. Similarly, most telescope control systems that implement TPOINT terms do so by taking each one and applying it in sequence. For small corrections this works well, and in practice it takes large collimation or polar axis errors to cause any noticeable mismatch between the two models (i.e. as fitted and as applied).

However, TPOINT provides an alternative fitting strategy that removes the distinction between the fitted and applied models. This is called the "rigorous fitting" method, and it is brought into play by including in the INDAT file one of the option records `': EQUAT'`, `': ALTAZ'` or `': GIMBAL` $z\ y\ x$`.'` The rigorous fitting method works as follows.

All TPOINT terms are implemented internally as adjustments to a basic 7-term model. This model, which applies to both equatorial and altazimuth mounts (and the "generalized gimbal" mount, further consideration of which will be postponed until the next section), consists of the six basic geometrical terms plus vertical deflection. The seven terms are, in telescope-to-star order, the two index errors, the vertical error, the two non-perpendicularities, and the two mount misalignment angles. In the equatorial case, the terms are −IH, ID, FLOP, −CH, −NP, −MA, ME. For an altazimuth, the terms are IA, IE, FLOP, CA, NPAE, AW, AN. TPOINT includes routines which apply the 7-term model in exactly the same way that a telescope control system would;[9] if the mount type has been specified, through the appropriate INDAT option record, the basic 7-term model is used during the fitting process in a close emulation of operational conditions.

The POX and POY pointing terms (Section 5.12), which allow for an off-axis pointing reference such as a guiding chip or autoguider probe, require rigorous fitting and hence the mount type to be declared in the INDAT file.

n.b. In special circumstances it is necessary for TPOINT to impose selection of the rigorous fitting method. If no mount type has been explicitly specified, and if observations beyond the pole/zenith are included, either EQUAT (INDAT format 1-3) or ALTAZ is assumed. Only the first such record will caused the override, and then only if no explicit option record was included in the INDAT file.

5.11   The generalized gimbal mount

TPOINT is applied as a rule to straightforward equatorial or altazimuth mounts. Where the mounting is unconventional, for example involving HET- or Arecibo-like arrangements

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[9]In fact the TPOINT routines are specifically designed for use in a telescope control system. The entire suite of modeling routines can be used in the "pointing kernel" portion of such a TCS, establishing an end-to-end tautology between the model that is fitted and the model that is used operationally. The scheme is implemented in the Tpoint Software product TCSpk.

or some form of coelostat, the harmonic terms may allow appropriate expressions to be formulated. An important intermediate case is that of the "generalized gimbal", where the mount is a conventional two-axis system but aligned neither to the pole nor the zenith. One example is the alt/alt mount, where the polar axis is horizontal; another is the type of tracking dish which can be tilted so that the target will bypass its blind spot. TPOINT provides support for the generalized gimbal case, essentially by treating it as a variety of altazimuth.

The generalized gimbal is specified by including a `': GIMBAL` z y x `'` option record in the INDAT file. The three (mandatory) arguments z y x are the Euler angles (in degrees) which specify the nominal mount orientation with respect to Az/El. The triad is right-handed, with its its z-axis pointing towards the positive pole and the x-axis pointing to zero longitude. The starting point is with the z-axis pointing upwards and the x-axis pointing south. The rotations, first about the z-axis, then y and finally x, are positive when anticlockwise as seen looking back towards the origin from the positive region of the axis.

The result of specifying the mount orientation in this way is that all the pointing terms and graphs that refer to azimuth or elevation in fact refer instead to the corresponding mount angles, "roll" and "pitch". (The exception is zenith distance, which *always* means with respect to the sky.) This means that effects in collimation, azimuth axis tilt, nonperpendicularity and so on are modeled and plotted using the ordinary Az/El nomenclature, thus avoiding the need for extra terms and plots. (The one "missing" option sacrificed by this ruse is that any effects in true azimuth cannot be modeled or plotted; however, this will rarely matter.)

Note that an equatorial mount could be analyzed by declaring it as a gimbal with angles of 0, $90° - \phi$, 0. The effect would be that all the altazimuth graphs would resemble the corresponding equatorial ones.

5.12   Off-axis pointing origin

Almost all optical/IR altazimuth telescopes, and some equatorials, have instrument rotators. The most convenient choice of pointing model in such cases is one that refers to the rotator axis (see Section 4.2.1), so that for a given $[\alpha, \delta]$ the required $[Az, El]$ or $[h, \delta]$ demands are unaffected by rotator angle. TPOINT will deliver such a model if the pointing-test stars have been centered on the rotator axis. This normally requires a preliminary calibration, involving rotating the mount through 180° and adjusting the crosswires, camera or guide probe, or deducing which point in the field of the viewing device stays fixed on the sky. (n.b. Locating the rotator axis can be tricky, and always relies on accurate open-loop tracking.)

The viewing device, even if nominally central, may be not adjustable. The field center may be obscured – a gap between CCD chips perhaps. The viewing device may lie permanently

well off-axis. In all such cases it will be necessary to conduct the pointing test with the viewing device at some unknown location in the rotating focal place. This corresponds to the final option in the table at the end of Section 4.2.1, and introduces two special model terms called POX and POY, which are the $[x, y]$ coordinates of the pointing origin in the rotating focal plane.

In order for TPOINT to determine $[POX, POY]$, the mount type must be specified (see Section 5.10), and the observations must cover a range of rotator angles. The minimum is two angles, ideally 180° apart, but for an altazimuth it would be usual for the rotator to be active in order to stabilize the field orientation, and as long as stars all over the sky have been observed this will supply the necessary range of angles automatically.

The rotator angle (in degrees) is included in the INDAT records as the first *auxiliary reading,* and **must** be present in all records where POX and POY apply. Incorrect and confusing results will be obtained if no angle is supplied.

When the model is fitted *ab initio,* it will typically require an extra iteration or two as the interplay between $[POX, POY]$ and the rest of the model converges and the model settles down. The resulting $[POX, POY]$ coordinates are reported in units that correspond to arcseconds on the sky at the center of the assumed tangent-plane projection. As a rule, they will simply be discarded, having played their part in obtaining the rotator-axis-based model but having no intrinsic interest. However, if the viewing device – a guide probe, say – has $[x, y]$ readouts or a known location, then comparison with the TPOINT-fitted $[POX, POY]$ is potentially very useful. A pointing test involving multiple pointing origins (next paragraph) and/or multiple field orientations may provide enough data to establish the mapping between the TPOINT/TCSpk and nominal $[x, y]$ systems.

Using data subsets (Section 5.8), it is possible to include observations from multiple pointing origins. For example, observations from a pair of probes or guiding chips might be included in the INDAT file as subsets A and B, and their respective fitted coordinates would then be POX/A, POY/A, POX/B and POY/B. It is even possible to combine off-axis observations made at different foci (OTA, Nasmyth, coudé), requiring different ROT... option records to be included in the INDAT file at appropriate places. This would, of course, also require separate IE and CA (or ID and CH) terms for each of the rotators.

5.13   Batch mode

It is possible to run TPOINT entirely without operator input, by including in the working directory a copy of the file `procs.dat` where the procedure INIT, which in the supplied `procs.dat` is empty, contains appropriate TPOINT commands to perform the required processing and ends with two QUIT commands. In a typical case this special INIT procedure would include one or more INDAT commands to read in observations and one or more OUTMOD commands to write fitted models to files. A special `tpoint.ini`

file (Section 8), also in the working directory, is normally also needed, containing the commands `short_report 2` to suppress all output and `script_abort 0` to prevent aborts if errors occur.

An example of such an INIT "batch" script would be one that fits an input file to a series of models of increasing elaboration, writing a model file for each. The same script will then work for input files containing any number of observations from 1 upwards. For a single observation, a model comprising only zero-points (IH and ID for an equatorial, IA and IE for an altazimuth) can be fitted, and the other models (that will have failed) ignored. For two observations the mount misalignment terms (ME, MA or AN, AW) can also be added, and so on. By means of this technique automatic self-alignment capabilities can be developed.

6   HOW TO ALIGN YOUR POLAR AXIS

The polar axis of an equatorial mount is nominally parallel to the axis of rotation of the Earth, and therefore points towards the celestial pole. However, refraction causes the celestial pole to appear slightly higher in the sky than it would in the absence of an atmosphere; it turns out that it is best to align the polar axis to this "refracted pole", rather than the true pole. This particular choice of alignment minimizes field rotation effects in the polar region and restores the standard 15″ per sidereal second tracking rate for the zenith region.

A perfect equatorial mounting, with the polar axis pointing at the true, unrefracted, pole, would correspond to a TPOINT model where all the coefficients are zero. Consequently, if the polar axis is raised slightly to align it with the refracted pole, the TPOINT model will have a non-zero ME coefficient. The following table shows what value of ME to aim for; it lists how far, in arcseconds, the celestial pole is raised by refraction, for observing sites at different latitudes and heights above sea level.

latitude	0m	250m	500m	750m	1000m	1250m	1500m	1750m	2000m	2500m	3000m	4000m
85	5	5	5	5	4	4	4	4	4	4	4	3
80	10	10	9	9	9	9	8	8	8	8	7	7
75	15	15	14	14	14	13	13	13	12	12	11	10
70	20	20	19	19	18	18	17	17	17	16	15	14
65	26	25	25	24	24	23	22	22	21	20	19	17
60	32	31	31	30	29	28	28	27	26	25	24	22
55	39	38	37	36	35	34	34	33	32	30	29	26
50	47	46	45	43	42	41	40	39	38	36	35	31
45	56	54	53	52	50	49	48	47	46	43	41	37
40	66	65	63	62	60	59	57	56	54	52	49	45
35	80	78	76	74	72	70	68	67	65	62	59	53
30	96	94	92	89	87	85	83	81	79	75	71	65
25	119	116	113	110	108	105	102	100	98	93	88	80
20	152	148	145	141	138	134	131	128	125	118	113	102
15	205	200	195	190	185	181	176	172	168	160	152	138
10	305	298	290	283	276	270	263	257	250	238	227	206
degrees	0ft	820ft	1640ft	2460ft	3280ft	4100ft	4920ft	5740ft	6560ft	8200ft	9840ft	13120ft

In the **northern hemisphere**, the ideal ME value for a particular telescope is **minus** the figure in the above table. For example, an equatorial telescope mount at 40° latitude and 500 meters above sea level would ideally have ME= −63″. If TPOINT estimated that ME was about +150″, the correct action to take would be to *raise* the polar axis by 150 − (−63) = 213 arcseconds.

In the **southern hemisphere**, the ideal ME value for a particular telescope is **plus** the figure in the above table. For example, an equatorial telescope mount at −35° latitude and 250 meters above sea level would ideally have ME= +78″. If TPOINT estimated that ME was about +181″, the correct action to take would be to *lower* the polar axis by 181 − 78 = 103 arcseconds.

The other polar axis misalignment term, MA, is more straightforward: the ideal value is always zero. In either hemisphere, an MA value of (say) +93″ could be eliminated by rotating the mount $93″/\cos\phi$ anticlockwise (as seen from above), where ϕ is the latitude of the site. Conversely, a negative MA value would require a clockwise adjustment.

The recommended procedure for adjusting the polar axis of a permanently-mounted equatorial telescope mount is therefore as follows:

1. Carry out a pointing test. Half a dozen stars, scattered around the sky, will be enough for a preliminary assessment, but a full test of 30-50 stars will give a more accurate final result.

2. Use TPOINT to analyze the test data. For a preliminary assessment the sequence of commands will be simply:

INDAT *file*	Read the pointing data file.
.EQUAT	Standard model for an equatorial.
FIT	Fit the standard 6-term model.

3. Look up the ideal ME value from the above table, paying attention to the sign (minus in the northern hemisphere).

4. Subtract the ideal ME value from the value which TPOINT reported, and raise (northern hemisphere) or lower (southern hemisphere) the polar axis by this amount.

5. Rotate the mount by $MA/\cos\phi$ arcseconds, anticlockwise if MA has a plus sign, otherwise clockwise.

6. Repeat Steps 1 and 2 to confirm that ME is now close to the desired value and MA is close to zero.

For telescopes that are not permanently mounted, the procedure can be adapted and simplified to allow rapid re-alignment of the polar axis prior to each observing session:

1. First characterize your telescope by doing a full TPOINT analysis, based on at least one comprehensive test of 30-50 stars. This will identify and calibrate and geometrical, cyclic and flexure terms. These terms would not be expected to change much with time, in contrast to the polar axis errors, ME and MA, the zero-point errors, IH and ID, and the collimation error, CH.

2. At the start of each observing session, make a preliminary alignment of the polar axis and then carry out a very short pointing test. In principle just three stars are enough. Use TPOINT to analyze the results, but with the model found in Step 1 as a fixed starting point. For example, if your pointing model included the terms HHSH, HHCH, TF and FO as well as the standard 6-term geometrical model (IH, ID, NP, CH, ME, MA), the sequence of commands will be:

INDAT *file*	Read the pointing data file.
.EQUAT	Standard model for an equatorial.
USE HHSH HHCH TF FO	The rest of the model.

```
NP -103                   Set NP to the value found in Step 1.
TF 38                     Set TF to the value found in Step 1...
...                       ...similar commands for FO, HHSH etc.
FIX                       Prevent the terms being changed...
USE IH ID CH ME MA        ...except for these five.
FIT                       Fit the terms that change from night to night.
```

(This can all be preprogrammed into your `procs.dat` procedure library to avoid unnecessary typing.)

3. Take the ME value which TPOINT reported (in arcseconds), and raise (northern hemisphere) or lower (southern hemisphere) the polar axis by this amount.

4. Rotate the mount by $\mathrm{MA}/\cos\phi$ arcseconds, anticlockwise if MA has a plus sign, otherwise clockwise.

5. If you wish, repeat Step 2, to confirm that ME and MA are now close to zero.

(The difference between the true pole and refracted pole has been neglected in this simplified procedure.)

7 REFERENCE SECTION

7.1 Commands

This section contains a description of every TPOINT command, in alphabetical order. A quick reference list is given at the end of the document.

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coeff	set/inquire coefficient value	*coeff*

FUNCTION :

The value of a coefficient in the current model may be set or inquired by using its name as the command.

COMMAND :

> *coeff value*

where *coeff* is the name of the coefficient, and *value* is the value.

NOTES :

If no argument is supplied, the coefficient is unaltered – merely logged.

In most cases *value* is in arcseconds; a few terms have dimensionless coefficients.

The coefficient name is usually just the name of a pointing term but may optionally be followed by a forward slash and a data subset name (see Section 5.8). The resulting string behaves as a coefficient name in its own right, so that coefficients ʹAWʹ, ʹAW/060331ʹ and ʹAW/060401ʹ are separate modeling terms and may all be present in the model at the same time.

ADJUST	select model direction	**ADJUST**

FUNCTION :

ADJUST allows one of two methods of applying the pointing model to be selected: whether the telescope positions are to be adjusted to fit the star positions or *vice versa*.

COMMAND :

> ADJUST T   to adjust the telescope positions
> or   ADJUST S   to adjust the star positions

NOTES :

If no argument is supplied, the method is unaltered – merely logged.

If the ADJUST command results in the direction being changed, the order of the terms in the pointing model is reversed to match.

A given set of data will not produce precisely the same coefficients if the model is reversed. The differences will be small unless one or more of the coefficients is very large – hundreds of arcseconds or more. Under these circumstances there is in any case a danger that TPOINT's formulation of the pointing terms does not match exactly the way the model is implemented in the control software of the telescope concerned. Large collimation corrections, in particular, may require more rigorous geometry than TPOINT normally offers (unless the "rigorous fitting" option is used), and detailed knowledge of field distortions.

The results of any previous FIT are not changed when ADJUST is used and, if a fresh FIT is to be carried out, the RESET command should be used first in order to eliminate the previous corrections.

APPEND   prepare to append observations   APPEND

FUNCTION :

APPEND prepares to concatenate the next set of pointing observations with the ones already input.

COMMAND :

> APPEND ON   next set of observations will be appended
> or APPEND OFF   cancel previous APPEND request

NOTES :

The argument defaults to ON.

The new data will be appended when the next INDAT command is executed.

At the time an APPEND request is made, a set of pointing observations must already be present in the data list.

CALL   call a library procedure   CALL

FUNCTION :

CALL calls a TPOINT library procedure.

COMMAND :

CALL *procedure*

where *procedure* is the name of the procedure to be called (1–10 characters). An alternative, shorthand, way of calling a procedure is to type:

.procedure

with or without spaces between the period and the procedure name.

CAPT enable/disable captions CAPT

FUNCTION :

CAPT enables or disables plotting of graph captions.

COMMAND :

	CAPT ON	enable plotting of captions
or	CAPT OFF	disable plotting of captions

NOTES :

The argument defaults to ON.

The motivation for disabling caption plotting may be to save time, or to avoid having the same caption repeated on a multi-plot display.

CHAIN apply terms sequentially CHAIN

FUNCTION :

CHAIN is used to indicate which terms are to be evaluated in sequence to their immediate predecessor in the model, each such term then being a function of the position as adjusted by the preceding term.

COMMAND :

CHAIN *coeff1 coeff2* etc.

where the arguments are the names of the coefficients to be CHAINed to their predecessors.

NOTES :

If no arguments are supplied, all the terms in the model are CHAINed.

If any argument is unrecognized, the entire command is rejected.

The converse command is PARAL, which allows more than one term to be calculated from a common starting position.

CLIST   list pointing coefficients   **CLIST**

FUNCTION :

CLIST lists the names of the current coefficients, their values, and whether they are fixed or floating. Here is an example:

```
 1     IA      -257.859    fixed
 2     IE      +383.760    1.674   /A
 3     IE      +431.220    1.660   /B
 4     IE      +429.013    1.647   /C
 5     HASA      -1.514    0.223
 6     HACA      -4.918    0.206
 7     HESE     -27.618    1.234
 8     HECE     +31.412    1.275
 9     HECA2     -0.577    0.149
10     HESA3     +0.928    0.141
11     NPAE     -14.722    1.232
12     CA       +20.339    1.670   /A
13     CA      +191.418    1.660   /B
14     CA      +190.927    1.651   /C
15     AN       -25.265    0.275   /A
16     AN       -32.479    0.195   /B
17     AN       -30.550    0.204   /C
18     AW       +14.751    0.303   /A
19     AW       +16.128    0.204   /B
20     AW       +10.674    0.186   /C
```

The model includes one fixed term, IA, the remaining terms being available for fitting. Seven of the terms (HASA, HACA, HESE, HECE, HECA2, HESA3 and NPAE) form a "core" that is common to all the observations. Four additional terms (IE, CA, AN and AW) appear in separate instances for three data subsets A, B and C (see Section 5.8).

CLOBBER   control file overwrite prompting   **CLOBBER**

FUNCTION :

CLOBBER controls whether attempts to overwrite an existing file require operator confirmation.

COMMAND :

> CLOBBER ON   overwrite silently
> or   CLOBBER OFF   don't overwrite unless operator confirms

NOTES :

The argument defaults to ON.

The state when TPOINT is started is CLOBBER OFF.

The command is useful if a pre-programmed set of responses is being used, avoiding unforeseen requests for confirmation.

ECHO   enable/disable command echoing   **ECHO**

FUNCTION :

ECHO enables or disables the echoing of commands to the screen during execution of library procedures.

COMMAND :

	ECHO ON	enable command echoing
or	ECHO OFF	disable command echoing

NOTES :

The argument defaults to ON. However, echoing is disabled when TPOINT is started.

Echoing is useful for debugging, but can clutter the screen at other times.

END   terminate the TPOINT session   **END**

FUNCTION :

END terminates TPOINT.

NOTE :

Additionally, Q, QUIT and QU are interpreted as END commands.

FAUTO   automatic modeling   **FAUTO**

FUNCTION :

   FAUTO carries out a search for terms which improve the pointing for the current
   data set, in the process detecting and MASKing any outliers among the observations.

COMMAND :

                 FAUTO n

   where n is the highest harmonic to be considered (default 8).

NOTES :

   For small numbers of observations, simple models are tried, using basic terms only.
   This enables sensible results to be obtained for a handful of stars (even just one or
   two). Above a few dozen stars, an exhaustive search, up to the specified harmonic,
   is carried out. Formal statistical tests are applied, to reject (i) terms of dubious
   benefit and (ii) observations that are inconsistent with the emerging model. The
   criteria are quite conservative, such that terms and observations to which a human
   modeler might give the benefit of the doubt are rejected.

   In all cases, any MASKed observations are reactivated before the modeling takes
   place; if this behaviour is not desired, a PURGE must be applied as a preliminary
   step. After the modeling has taken place, any observations considered to be outliers
   are left in a MASKed state.

   The full modeling procedures (*i.e.* when the number of points exceed a few dozen)
   accept any pre-existing model as a starting point. The original terms may or may
   not survive, depending on how they fare when tested against the range of terms
   tried out during the modelling process. This feature makes it worthwhile to repeat
   an *ab initio* FAUTO, in the expectation that the presence of a preliminary model
   will make the evaluation of subsequently added terms more reliable. By the same
   token, if a pre-existing model is available, it may be helpful to load it before invoking
   FAUTO.

FIT   fit model to observations   **FIT**

FUNCTION :

   FIT computes the coefficient values for the current pointing model which fit the
   observations best, and updates either the adjusted telescope coordinates or the
   adjusted star coordinates depending on which of these two options is in force (see
   the ADJUST command).

COMMAND :

FIT   to perform a normal fit
or   FIT N   to apply the current model without fitting

NOTES :

If two terms in the model are too highly correlated to be reliably distinguished, this is reported by FIT so that one of them can be eliminated from the model. The FITTOL command provides control over the treatment of such ill-conditioned cases, allowing the acceptance criterion used by the "singular value decomposition" fitting method used in FIT to be specified. If this criterion is set to zero, by means of a FITTOL 0 command, the fit is simply a conventional least-squares approximation, and any highly correlated terms will be awarded meaningless, large and mutually cancelling values, accompanied as a rule by a poor overall RMS result. With a FITTOL parameter of (for example) 0.005, such correlated terms are kept under control and the model is sound.

If all the coefficients have been FIXed, the result of the FIT command is simply to recompute the residuals, and in this case FIT and FIT N are equivalent.

FITTOL   set ill-conditioning tolerance   **FITTOL**

FUNCTION :

FITTOL specifies and reports the acceptance criterion for the singular value decomposition algorithm used in the FIT command.

COMMAND :

FITTOL v

where v is the tolerance used by the FIT command to decide whether action is to be taken to keep a poorly determined solution under control.

NOTES :

A tolerance value v between zero and 0.01 is recommended. The initial value is 0.001.

A zero tolerance value means that FIT produces a conventional least-squares result, with no protection against ill-conditioning. However, it can be useful to try this, as it may help to expose highly correlated terms.

If no argument is supplied, the current tolerance is reported but not changed.

FIX   fix the specified terms   **FIX**

FUNCTION :

FIX excludes one or more terms from the fit but not from the model.

COMMAND :

> FIX *coeff1 coeff2* etc.

where the arguments are the names of the coefficients to be frozen at their current values.

NOTES :

If no arguments are supplied, the whole model is fixed.

If any argument is unrecognized, the entire command is rejected.

FLIST   export results   **FLIST**

FUNCTION :

FLIST exports to a file a list of the pointing observations and the current residuals. This may useful for further graphics and analysis outside TPOINT.

COMMAND :

> FLIST *outputfile*

where the argument is the name of the file to be written.

NOTES :

The FLIST output is intended to be useful in cases where further analysis is to take place outside TPOINT.

Each record (apart from the concluding ′END′ record) corresponds to one active observation. Its fields, with the corresponding C `scanf` conversion specification, are as follows:

`%4d`	observation number
`%c`	below pole flag
	space
`%2d`	star h hours
`%3d`	star h minutes
`%8.4f`	star h seconds
	space
`%c`	star δ sign
`%2d`	star δ degrees
`%3d`	star δ arcminutes
`%7.3f`	star δ arcseconds
`%9.3f`	star A (degrees, N thru E)
`%8.3f`	star ζ (degrees, observed)
`%9.3f`	dX = east-west error
`%9.3f`	dD = north-south error
`%9.3f`	dS = left-right error
`%9.3f`	dZ = up-down error
`%9.3f`	dR = radial error

The listing produced is similar to that displayed by the SLIST command, except that the resolution is higher, there are no headers or footers, inactive observations are not listed and subset membership is not marked.

The SLIST command options (error threshold, paged output) have no FLIST counterparts.

FRAME   enable/disable frames   **FRAME**

FUNCTION :

FRAME enables or disables the plotting of graph frames. A frame is a rectangular box drawn just inside the edge of the plotting zone.

COMMAND :

	FRAME ON	enable plotting of frames
or	FRAME OFF	disable plotting of frames

NOTE :

If no argument is supplied, the default is frames enabled.

G   plot residuals   **G**

FUNCTION :

G plots the pointing residuals as the component in one coordinate against that or another coordinate.

COMMAND :

G *ydata xdata scale*

where *ydata* is one of the following:

H	pointing error in HA
X	pointing error EW
D	pointing error in Dec
P	pointing error corresponding to HA/Dec nonperpendicularity
A	pointing error in azimuth
S	pointing error horizontally
Z	pointing error in zenith distance (sky)
E	pointing error in elevation (mount)
V	pointing error corresponding to Az/El nonperpendicularity
R	total pointing error

and *xdata* is one of the following:

H	hour angle
D	declination
A	azimuth
Z	zenith distance (sky)
E	elevation (mount)
Q	parallactic angle
N	observation number

The optional argument *scale* indicates the vertical plotting scale: it is the absolute value of the largest residual to be plotted. In default, a scale is chosen automatically to suit the data.

NOTES :

The residuals are in the sense telescope minus "observed".

For the generalized gimbal case, "azimuth" and "elevation" refer to the mount coordinates. However, "zenith distance" always means with respect to the vertical.

Fig. 3 includes an example of a G plot.

GAM   look for axis misalignment   GAM

FUNCTION :

GAM plots the pointing residuals interpreted as a misalignment of either the polar or the azimuth axis. Two superimposed graphs are plotted, showing respectively (i) the orientation and (ii) the amount of misalignment of the polar or azimuth axis that would produce each of the residuals. Graph (i) consists of the orientations calculated for each observation plotted in histogram form. Graph (ii) shows the component of pointing residual for each observation in the direction of the mean orientation. The x-axis of the two graphs is the hour angle or azimuth.

COMMAND :

> GAM *type scale*

The *type* is E or Q for equatorial and A or Z for Az/El. The equatorial plots have hour angle as their x-axis and look for misalignment of a polar axis. The Az/El plots have azimuth as their x-axis and look for misalignment of an azimuth axis. The Q and Z options suppress an informational message which is normally sent to the screen. This argument defaults to E.

The *scale* indicates the plotting scale for the amount-of-misalignment plot, and is the absolute value of the largest residual to be plotted. In default, a scale is chosen automatically to suit the data.

NOTES :

When constructing the histogram and computing the mean orientation, each individual orientation is weighted by the size of the supposed axis misalignment.

Fig. 3 contains examples of GAM plots, equatorial and altazimuth.

GC   graphics device control   GC

FUNCTION :

GC provides special control functions for the graphics device. Three functions are supported:

> GC [C]   clears the display surface
> GC P [*file*]   writes a PostScript file (colored pens)
> GC B [*file*]   writes a PostScript file (all pens black)

NOTES :

For the 'P' and 'B' options, the filename defaults to that specified in the initialization file `tpoint.ini` (Section 8).

Using `GC P` or `GC B` when displaying multiple plots may produce unexpected black rectangles in the PostScript output. The cause is to do with the way individual regions of the plotting window are cleared. The cure is to precede the plotting with the command `CLRNG OFF` and then `CLRNG ON` afterwards.

GDIST   plot error distributions   GDIST

FUNCTION :

GDIST plots distributions of the pointing residuals.

NOTES :

The histograms labelled X, D, S and Z are the components east-west, north-south, left-right and up-down; the histogram labelled R is for the total pointing errors.

Fig. 3 contains an example of a GDIST plot.

GHYST   hysteresis plot   GHYST

FUNCTION :

GHYST attempts to expose hysteresis by assuming that the direction (and perhaps distance) from the current observation to the previous observation determine the direction (and perhaps size) of the effect. The format is a polar plot, with north at the top if the equatorial option has been selected, or up at the top if the altazimuth option has been selected. Each observation (except the first) is plotted as a square marker, from the center of which comes a line indicating the pointing residual. The position of the marker shows in what direction the telescope had to move in order to travel from the previous star, and how far (on a logarithmic scale).

COMMAND :

GHYST *type scale*

The *type* is E or Q for equatorial and A or Z for Az/El. The equatorial plot has north at the top, whereas the Az/El plot has up at the top. The Q and Z options suppress an informational message which is normally sent to the screen. This argument defaults to E.

The *scale* is the residual in arcseconds to give a vector of nominal maximum length. This defaults to the largest actual residual providing it is reasonable.

NOTES :

A numerical estimate of the hysteresis is made and reported. It is obtained by rotating each pointing residual by the orientation of the preceding telescope movement, accumulating vectorially, and finally dividing by the number of active observations.

Note that various important but dubious assumptions are being made:

- The order of observations in the data list is the same as in reality.
- The telescope travelled directly from one star to the next, along a straight line in Cartesian cylindrical coordinates.
- Any hysteresis comes from the large scale movements between observations and is unaffected by small scale adjustments during acquisition.

Residuals are in the sense telescope minus "observed".

For equatorial mounts, there may be hysteresis in both HA/Dec and Az/El, and it is worth trying both. Altazimuth mounts are not likely to display any HA/Dec effects, and the (default) E option is not appropriate for this case.

Because most observing sequences tend to favor particular telescope movement directions the graph produced by GHYST is cluttered, with many points bunched together. The appearance may be improved by using the MARKH command to reduce the size of the markers.

Fig. 3 contains examples of GHYST plots, equatorial and altazimuth.

GMAP   Cartesian cylindrical plot   **GMAP**

FUNCTION :

GMAP draws a map of the pointing residuals as error vectors on a Cartesian Cylindrical projection.

COMMAND :

> GMAP *type scale*

The *type* is E for equatorial and A for Az/El. This argument defaults to E.

The *scale* is the residual in arcseconds to give a vector of nominal maximum length. This defaults to the largest actual residual providing it is reasonable.

NOTE :

Fig. 4 contains examples of GMAP plots, equatorial and altazimuth.

GSCAT   scatter plot   GSCAT

FUNCTION :

GSCAT plots the pointing residuals as a scatter diagram. The plot resembles a view
of the telescope field, with points showing where each star would have appeared had
the telescope been set blind, using the current pointing model. The field can be one
in which north-south is at a fixed orientation, or one in which up-down (or in the
special case of a generalized gimbal the "pitch" coordinate) is fixed.

COMMAND :

GSCAT *type radius*

The *type* is E for equatorial and A for Az/El. The equatorial plot is relative to
east-west and north-south axes, whereas the Az/El plot is relative to left-right and
up-down axes. This argument defaults to E.

The *radius* is that of the scatter graph in arcseconds and must lie in the range
0.1–9999.9. It defaults to a suitable scale to display the data concerned.

NOTE :

Fig. 4 contains examples of GSCAT plots, equatorial and altazimuth.

GSMAP   azimuthal map   GSMAP

FUNCTION :

GSMAP draws a map of the pointing residuals as error vectors on an azimuthal
projection, either orthographic or Lambert equal-area.

COMMAND :

GSMAP *scale* =

where *scale* is the plotting scale, the residual in arcseconds to give a vector of
nominal maximum length, and = is the character '=', which selects the equal-area
projection.

NOTES :

The *scale* defaults to the largest actual residual providing it is reasonable.

If both arguments are used (selecting the equal-area projection as well as specifying
a scale) it doesn't matter whether the '=' character comes first or second.

Fig. 4 contains examples of GSMAP plots, orthographic and equal-area.

H   search for harmonics   **H**

FUNCTION :

H (or H1) searches for harmonic terms by fitting to a specified component of the pointing residuals functions $C_0 + C_1 \sin nA + C_2 \cos nA$, where n is an integer and A is a specified angle.

COMMAND :

$$H \quad r \quad a \quad n1 \quad n2$$

where r is one of the following components of pointing error:

H	pointing error in HA
X	pointing error EW
D	pointing error in Dec
P	pointing error corresponding to HA/Dec nonperpendicularity
A	pointing error in azimuth
S	pointing error horizontally
Z	pointing error in zenith distance (sky)
E	pointing error in elevation (mount)
V	pointing error corresponding to Az/El nonperpendicularity

a is one of the following angles:

H	hour angle
D	declination
A	azimuth
Z	zenith distance (sky)
E	elevation (mount)
Q	parallactic angle

and the optional arguments *n1* and *n2* are integers in the range 1–999.

NOTES :

The search consists of trying out terms *Hrfan*, where the character r represents a component of pointing error, f is $'S'$ or $'C'$, standing for "sine" or "cosine", the character a represents the argument of the harmonic term and n is the sequence of integers from *n1* to *n2* inclusive. Each trial fit includes a constant term (not reported) and the S and C terms for the r, a and n combination under test.

The two numbers *n1* and *n2* can be in either order. The default for *n1* is 1; the default for *n2* is *n1* + 8 (up to the maximum).

The report includes the amplitudes of the sine and cosine terms for the frequency under test, and an estimate of the standard deviation. Terms of higher statistical significance are flagged as possible additions to the current model.

The H command should be used with circumspection. It is normally wise to try out only one new harmonic frequency at a time, and even then it is common to find that a promising term loses much of its statistical significance once it takes its place in the model and competes with other terms. The command is most useful as an adjunct to the G command, to follow up suspicions of periodic effects gleaned from visual inspection of the various graphs.

H2   search for and list cross-harmonics   H2

FUNCTION :

H2 searches for harmonic terms by fitting to a specified component of the pointing residuals functions $C_0 + C_1 \sin na + C_2 \cos na + C_3 \sin NA + C_4 \cos NA$, where n and N are integers and a and A are specified angles. (The H2A command – see below – does the same but, instead of listing the terms, adds the one with the biggest amplitude to the current model.)

COMMAND :

> H2   *r a A n1 n2 N1 N2*

where r is one of the following components of pointing error:

H	pointing error in HA
X	pointing error EW
D	pointing error in Dec
P	pointing error corresponding to HA/Dec nonperpendicularity
A	pointing error in azimuth
S	pointing error horizontally
Z	pointing error in zenith distance (sky)
E	pointing error in elevation (mount)
V	pointing error corresponding to Az/El nonperpendicularity

a and A are, in each instance, one of the following angles:

H	hour angle
D	declination
A	azimuth
Z	zenith distance (sky)
E	elevation (mount)
Q	parallactic angle

and the optional arguments *n1, n2* and *N1, N2* are pairs of integers that specify the range of frequencies to be searched for the angle argument in question. The acceptable ranges are 1-99 for *n1* and *n2*, and 1–9 for *N1* and *N2*, with the additional restriction that if either of *n1* and *n2* is more than 9 then *N1* and *N2* must both be 1.

NOTES :

The search consists of trying out terms *HrfanFAN*, where the character *r* represents a component of pointing error, *f* and *F* are ′S′ or ′C′, standing for "sine" or "cosine", *a* and *A* represent the argument of the harmonic factor and *n* and *N* are the sequence of integers from, respectively, *n1* to *n2* and *N1* to *N2* inclusive. Each trial fit includes a constant term (not reported) and the ′S′ and ′C′ terms for the *r*, *a*, *A*, *n* and *N* combination under test.

The numbers in each pair *n1,n2* and *N1,N2* can be in either order. The defaults for *n1* and *n2* are 1; the defaults for *n2* and *N2* are *n1*+8 and *N1*+8 (up to the maxima).

The report includes the amplitude of the cross-harmonic term for the frequency under test and an estimate of its standard deviation. Terms of higher statistical significance are flagged as possible additions to the current model. The report is sorted into order of increasing amplitude, so that the most promising candidates appear last; however, the ratio between the amplitude and standard deviation is a more reliable guide than the amplitude alone.

The H2 command should be used with circumspection. It is normally wise to try out only one new term at a time, and even then it is common to find that a promising term loses much of its statistical significance once it takes its place in the model and competes with other terms. The command is most useful as an adjunct to the G command, to follow up suspicions of periodic effects gleaned from visual inspection of the various graphs.

H2A search for cross-harmonics and add best to model **H2A**

FUNCTION :

Like the H2 command (see above), H2A searches for harmonic terms by fitting to a specified component of the pointing residuals functions $C_0 + C_1 \sin na + C_2 \cos na + C_3 \sin NA + C_4 \cos NA$, where *n* and *N* are integers and *a* and *A* are specified angles. However, whereas H2 lists the terms, H2A adds the biggest one to the current model.

COMMAND :

> H2A *r a A n1 n2 N1 N2*

where *r* is one of the following components of pointing error:

H	pointing error in HA
X	pointing error EW
D	pointing error in Dec
P	pointing error corresponding to HA/Dec nonperpendicularity
A	pointing error in azimuth
S	pointing error horizontally
Z	pointing error in zenith distance (sky)
E	pointing error in elevation (mount)
V	pointing error corresponding to Az/El nonperpendicularity

a and *A* are, in each instance, one of the following angles:

H	hour angle
D	declination
A	azimuth
Z	zenith distance (sky)
E	elevation (mount)
Q	parallactic angle

and the optional arguments *n1*, *n2* and *N1*, *N2* are pairs of integers that specify the range of frequencies to be searched for the angle argument in question. The acceptable ranges are 1-99 for *n1* and *n2*, and 1–9 for *N1* and *N2*, with the additional restriction that if either of *n1* and *n2* is more than 9 then *N1* and *N2* must both be 1.

NOTES :

Only if the best term is of more than 2σ significance is it added to the model.

See the H2 command for further details.

HELP   enter HELP session   **HELP**

FUNCTION :

HELP enters a HELP session.

COMMAND :

HELP *topic*

where *topic* is the HELP topic to be displayed.

NOTES :

If no *topic* is specified, the top level HELP topics are displayed.

The TPOINT online HELP library is hierarchical in structure, and is explored by typing either the keyword for the required topic or `Enter` to return to the previous level. To end the HELP session, keep pressing `Enter` until the $'*'$ prompt reappears.

INDAT   read file of observations   **INDAT**

FUNCTION :

INDAT reads a file of telescope pointing observations and converts it into the internal form required for analysis.

COMMAND :

> INDAT *file subset*

where *file* is the name of the file of pointing observations and *subset*, if present, is the name of the (initial) data subset to which the observations belong (see Section 5.8).

NOTES :

The file name that is supplied is automatically prefixed and/or suffixed as necessary before use. It defaults to the previous name that was successfully used.

The internal form generated by INDAT is called the *data list*.

Several input formats are supported. Details are given in the Section 4.

INMOD   read model from file   **INMOD**

FUNCTION :

INMOD reads a pointing model from a file.

COMMAND :

> INMOD *file*

where *file* is the name of the file containing the model.

NOTES :

Model files can be written by the OUTMOD command.

Any existing model is superseded by the one input.

In addition to the model itself, the file contains a caption, a number of observations, and an RMS; these latter items are not used by INMOD.

INPRO   input a procedure library   **INPRO**

FUNCTION :

INPRO inputs a procedure library, adding to and/or updating the library already
present.

COMMAND :

> INPRO *file*

where *file* is the name of the procedure file to be input.

NOTES :

Any procedures found in the specified file that have counterparts in the already
loaded library take precedence.

If a filename is not specified, the procedure library which was input at the start of
the TPOINT session is re-read. In this case, subsequent additions are lost.

This command is not permitted within procedures.

A useful sample procedure library is supplied with the TPOINT system and is
loaded automatically when the system is initialized. The command INPRO with no
arguments will reload it and erase any changes made during the session.

The initialization procedure INIT, called when TPOINT is first started, is **not** called
when INPRO is used.

INST   input a star catalog   **INST**

FUNCTION :

INST inputs a star catalog, replacing any previous one.

COMMAND :

> INST *file*

where *file* is the name of the catalog file to be input.

NOTE :

If a filename is not specified, the star catalog which was input at the start of the
TPOINT session is re-read.

A small star catalog is supplied with the TPOINT system and is loaded automat-
ically when the system is initialized. The command INST with no arguments will
reload it.

LOSE <div align="center">remove terms from model</div> **LOSE**

FUNCTION :

LOSE removes one or more terms from the pointing model.

COMMAND :

> LOSE *coeff1 coeff2* etc.

where *coeff1 coeff2* etc. are the names of the terms to be eliminated.

NOTES :

If no arguments are supplied, the whole model is discarded.

If any argument is unrecognized, the entire command is rejected.

MARK <div align="center">Specify pen for MASKed points</div> **MARK**

FUNCTION :

MARK assigns all MASKed observations to a specified plotting pen (and then UN-MASKs them).

COMMAND :

> MARK *n*

where *n* is the pen number.

NOTES :

The default is the pen used for normal points.

The actual colors are dependent on the implementation of the TPOINT graphics subsystem being used. The current selections can be inspected by executing the command PENS.

To revert to normal plotting, MASK all observations and then execute MARK without an argument.

MARKH   specify marker height   MARKH

FUNCTION :

MARKH specifies the marker height for plotting.

COMMAND :

                MARKH h

where h is the marker height in plotting units.

NOTES :

The default is 0.2.

The markers controlled in this way are the square and asterisk symbols used by the G... commands.

The normal use of MARKH is to reduce the marker size where the number of observations is large and the default size gives a cluttered result.

MASK   flag selected observations inactive   MASK

FUNCTION :

MASK flags selected pointing observations inactive. The selection is made by area of sky, total residual, or sequence number.

MASK/UNMASK can also be used to mark out selected observations temporarily for various purposes, such as assigning them to a specified data subset (via the SUBSET command) or plotting them in a different color (via the MARK command).

COMMAND :

           MASK *quantity condition value*
or   MASK *n1 n2*
or   MASK */subset1 /subset2...*

where the arguments are as follows:

	quantity	H (HA), D (Dec), A (Az), Z (ZD), E (El), R (radial error) or N (observation number)
	condition	L (less than) or G (greater than)
	value	cutoff value (hours for H, degrees for D, A, Z or E, arcseconds for R, number for N)
or	*n1*	first observation number
	n2	last observation number (defaults to *n1*)
or	*/subset...*	one or more data subset names

NOTES :

If the arguments are omitted, all observations are MASKed.

The inverse command is UNMASK.

Azimuths lie within the range 0 to 360°, reckoned from north through east.

Observation numbers:

- start at 1 and refer to all observations, whether or not currently active;
- can be given in either order.

EXAMPLES :

MASK H L 4	makes inactive all observations where hour angle is less than 4^h (60°)
MASK Z G 20	makes inactive all observations where zenith distance is greater than 20°
MASK N G 20	makes inactive all but the first 20 observations
MASK 3	makes inactive the 3rd observation
MASK 1 25	makes inactive the first 25 observations
MASK /A	makes inactive all the observations in subset A
MASK	makes all the observations inactive

MESLEV specify message level MESLEV

FUNCTION :

MESLEV allows the volume of messages going to the screen and to the log file to be restricted to a nominated "severity level".

COMMAND :

MESLEV *mess rept*

where *rept* and *mess* are the limiting message severity levels for the report and message devices respectively, each an integer in the range 0 to 5.

NOTES :

Different *rept* and *mess* values have the following effects:

> *mess/rept*
>> 0   don't suppress any messages
>> 1   suppress presentational messages
>> 2   . . . and informational messages
>> 3   . . . and warning messages
>> 4   . . . and application error messages
>> 5   suppress all messages including system errors

If the second argument is omitted, the existing setting for the report device remains in force. If both arguments are omitted, both values are set to zero.

This command is most useful for reducing the volume of messages during the execution of library procedures; during interactive use it is best to enable all messages.

MODOR   re-order the model terms   MODOR

FUNCTION :

MODOR places the current set of model terms into a suitable order, with plausible chained/parallel choices.

MVET   vet the current model   MVET

FUNCTION :

MVET reviews the current model to see if any terms can be removed without significant harm. A report is presented showing the terms in decreasing order of credibility, with any terms not considered beneficial flagged. The weakest of any such terms found can optionally be removed automatically. Any such terms found can optionally be removed, one at a time, up to a specified maximum.

COMMAND :

> MVET n

where the optional argument n is the maximum number of ineffectual terms to be removed from the model, defaulting to zero if n is absent or less than one. Once all the remaining model terms are judged to be beneficial, no further terms are removed.

NOTES :

The command will overwrite any existing coefficient values.

Because it performs multiple fits, the command consumes significant CPU time.

NEED   include must-have terms   **NEED**

FUNCTION :

NEED is very similar to USE except that formerly absent terms are left FIXed at zero. This is done in cases where the pointing correction is known to be applicable (for example index errors) but is of statistically insignificant amplitude. The presence of a term, but fixed at zero, makes it clear that the term has been considered but not used.

COMMAND :

> NEED *coeff1 coeff2* etc.

where the arguments are the names of the terms to be included in the model but, if absent, to be left FIXed and fixed at zero.

NOTES :

Any term already in the model is flagged to be fitted; in this case NEED cancels a prior FIX.

If no arguments are supplied, all terms currently in the model are flagged to be fitted.

If any argument is unrecognized, the entire command is rejected.

OUTDAT   write file for INDAT   **OUTDAT**

FUNCTION :

OUTDAT outputs the current pointing data as a file that can be read in by INDAT.

COMMAND :

> OUTDAT *file*

where *file* is the name of the file to be written.

NOTES :

Only active observations (those not rendered inactive via the MASK command) are output.

If the mount type has been declared, the corresponding option record is included in the file generated by OUTDAT. If the mount type is altazimuth or generalized gimbal, the observation records are written using INDAT's Format 4 (star and telescope [Az, El]). Otherwise, INDAT's Format 1 is used. (Note however that the

sidereal times are set to zero and, to match, the star right ascensions are fake, equal to minus the hour angle.)

The auxiliary readings associated with each observation are written, up to and including the last one that is non-zero.

If any observations are members of "data subsets" (see Section 5.8) corresponding D-records are inserted into the file at appropriate points.

OUTL   identify outlier candidates   OUTL

FUNCTION :

OUTL identifies one or more of the least typical observations, and optionally MASKs each one (*i.e.* temporarily removes it from the fit) if its "badness" is above a specified threshold.

COMMAND :

OUTL v n

where v is the "badness" value above which the observation is to be MASKed, and n is the maximum number of observations to be MASKed. If v is not specified, no observations are MASKed; if n is not specified, it defaults to one, which is the recommended value to use.

NOTE :

The command refits the current model at least once, which will overwrite any existing coefficient values.

OUTMEX   write model as spreadsheet line   OUTMEX

FUNCTION :

OUTMEX outputs the current model to a file in the form of a single line of fields separated by the $'|'$ (vertical bar) character, suitable for use in spreadsheet applications such as Microsoft Excel.

COMMAND :

OUTMEX *file*

where *file* is the name of the file to be written.

NOTE :

As well as writing the model information itself, OUTMEX stores the caption, number of stars used, the five RMS values (EW, NS, LR, UD and sky), the refraction constants, the "sampled PSD" (if the SAMSIG command has been used) and the list of MASKed observations excluded from the statistics.

OUTMOD   write model to a file   OUTMOD

FUNCTION :

OUTMOD outputs the current model to a file.

COMMAND :

> OUTMOD *file*   full model
> or   OUTMOD *file* S   session terms only

where *file* is the name of the file to be written.

NOTES :

The file can be read by means of the INMOD command.

The "session" terms, omitted when the S option is chosen, are those not normally needed in telescope control applications, namely POX and POY (Section 5.12) and terms that belong to a "data subset" (Section 5.8).

As well as writing the model information itself, OUTMOD stores the caption and (unless the S option has been chosen) the number of stars used, the five RMS values (EW, NS, LR, UD and sky), the refraction constants, the "sampled PSD" (if the SAMSIG command has been used) and the list of MASKed observations excluded from the statistics.

Here is an example model file as output by OUTMOD:

```
ALMA
T  337   1.7781     0.000
    IA        -257.8593     1.27618
    IE        +383.7603     1.67448   /A
    IE        +431.2202     1.66009   /B
    IE        +429.0133     1.64669   /C
    HASA        -1.5138     0.22269
    HACA        -4.9180     0.20624
    HESE       -27.6182     1.23436
    HECE       +31.4116     1.27476
    HECA2       -0.5766     0.14868
    HESA3       +0.9278     0.14120
    NPAE       -14.7216     1.23225
    CA         +20.3391     1.66955   /A
    CA        +191.4184     1.66019   /B
    CA        +190.9266     1.65091   /C
    AN         -25.2646     0.27476   /A
    AN         -32.4794     0.19485   /B
    AN         -30.5505     0.20432   /C
```

```
            AW          +14.7509      0.30254   /A
            AW          +16.1285      0.20362   /B
            AW          +10.6742      0.18607   /C
        END
```

The model includes one fixed term, IA, the remaining terms being available for fitting. Seven of the terms (HASA, HACA, HESE, HECE, HECA2, HESA3 and NPAE) form a "core" that is common to all the observations. Four additional terms (IE, CA, AN and AW) appear in separate instances for three data subsets A, B and C (see Section 5.8).

PARAL   apply terms in parallel   **PARAL**

FUNCTION :

PARAL is used to indicate which terms are to be evaluated in parallel to the immediately preceding term in the model. This allows several consecutive terms to use the same position as their starting point, rather than each successively adjusting the position before it is used by the next term.

COMMAND :

PARAL *coeff1 coeff2* etc.

where the arguments are the names of the terms to share starting points with their predecessors.

NOTES :

If no arguments are supplied, all the terms in the model use the same starting point – the initial, unadjusted position.

If any argument is unrecognized, the entire command is rejected.

The starting position for a term named in this command will be the adjusted position produced by the last term which is "chained" rather than "parallel". Thus the first term in a group of terms sharing a common starting point will, in fact, be "chained".

The converse command is CHAIN.

PENS   specify pens   **PENS**

FUNCTION :

PENS specifies and reports the pens used for plotting on the current graphics device.

COMMAND :

PENS *f c a l p o*

where the arguments are the pen numbers for:

f	frame
c	caption
a	axes
l	labels
p	points which are valid
o	points which are off-scale

NOTES :

Arguments default to the existing value. For example the command PENS,,9,,17 will change only the "axes" and "valid points" pens.

If any argument is invalid none of the pens are changed.

The actual colors and line styles are dependent on the implementation of the TPOINT graphics subsystem being used. Note that although colored pens may be used to produce both colored lines and text, pens giving dotted or broad lines may not produce analogous effects on text.

PERFCT   create ideal observations   **PERFCT**

FUNCTION :

PERFCT creates a list of artificial error-free pointing observations.

COMMAND :

        PERFCT ϕ

where ϕ is the telescope latitude to which the artificial observations will correspond, given as degrees, arcminutes, arcseconds.

NOTES :

The arcminutes and/or arcseconds may be omitted; in all cases the final field may have a decimal point and a fractional part. If the entire argument is omitted, the latitude found in the data list is used. If the data list is empty, latitude zero is used.

If a mount type (equatorial, altazimuth or gimbal) has been declared, the declaration stays in force. (The only way of reverting to the "undeclared" state is by reading a new file with INDAT which contains no declaration.)

PLTOFF   close plotting window   **PLTOFF**

FUNCTION :

PLTOFF closes the current plotting window and reverts to the previous one, if any.

COMMAND :

        PLTOF

PLTON   open plotting window   **PLTON**

FUNCTION :

PLTON opens a new plotting window.

COMMAND :

> or   PLTON *label*

where *label* appears as the name of the window.

NOTE :

If no plotting window is open when a graphing command is used there is an automatic PLTON.

PLTZ   select a plotting zone   **PLTZ**

FUNCTION :

PLTZ selects a plotting zone.

COMMAND :

	PLTZ	use full display surface
or	PLTZ *name*	use named region
or	PLTZ *x1 x2 y1 y2*	use numerically specified region

where *name* is the zone name (see below) and *x1 x2 y1 y2* specify the zone extent directly.

NOTES :

The zone *name* refers to a range of regular subdivisions of the display surface. For 3×3 partitioning, the names are TL, TC, TR, CL, CC, CR, BL, BC, BR (T=top, C=center, B=bottom, L=left, R=right). For 2×2 the names are TLQ, TRQ, BLQ, BRQ. For 2×1 the names are T, B, L, R.

If numeric parameters are supplied (all four are required) they specify the X range and Y range in a coordinate system where the display surface is a unit square with its origin at the bottom left-hand corner.

PURGE purge MASKed observations PURGE

FUNCTION :

PURGE removes inactive observations from the data list.

COMMAND :

PURGE

NOTES :

Once the inactive observations have been purged, they can be restored only by rereading the original file.

The numbering of a given observation may change as a result of the purge.

REPLEN specify report length REPLEN

FUNCTION :

REPLEN selects the report length option.

COMMAND :

REPLEN *option*

where *option* is either S for short or L for long (or N for no reports, not even the command prompt).

NOTES :

The default option is L.

REPLEN affects the volume of output from commands such as INDAT and SLIST.

RESET zero the pointing coefficients RESET

FUNCTION :

RESET sets all pointing coefficients to zero and removes all pointing corrections from the data list.

RETURN   return from a procedure   **RETURN**

FUNCTION :

RETURN returns from a library procedure.

NOTE :

A RETURN command issued from the command device results in an error message.

SAMSIG   estimate PSD by sampling   **SAMSIG**

FUNCTION :

SAMSIG reports the population standard deviation (PSD) of the current data set and model when estimated by sampling. The result is based on the residuals for each individual observation when that one observation has been excluded from the data set used for fitting – a procedure known as "jackknifing".

A "sampling randomness criterion" is also reported and is the formula-based PSD divided by the sampled PSD, expressed as a percentage. A high figure, near 100%, indicates that the data set is well-distributed; lower figures indicate that the observations are excessively clustered.

COMMAND :

                    SAMSIG

NOTES :

The procedure begins and ends by fitting the current model, which will overwrite any existing coefficient values.

Because SAMSIG performs one fit for every active observation, it consumes more CPU time than do most TPOINT commands.

SAY   display a message   **SAY**

FUNCTION :

SAY displays a message.

COMMAND :

                    SAY *string*

where *string* is the required one-line message, and consists of the whole of the command line following the command name but with leading and trailing blanks eliminated.

NOTE :

If the message contains lowercase characters, enclose it in single or double quotes.

SETCAP set the caption SETCAP

FUNCTION :

SETCAP sets the caption string.

COMMAND :

SETCAP *string*

where *string* is the required caption, and consists of the whole of the command line following the command name but with leading and trailing blanks eliminated.

NOTES :

If no argument is supplied the caption is set to a single space.

If the caption contains lowercase characters, enclose it in single or double quotes.

SHOW display parameters SHOW

FUNCTION :

SHOW displays and logs the current values of various TPOINT internal parameters.

NOTE :

The output from SHOW is a useful guide to some of the features of TPOINT, and includes the names of the commands used for changing the parameters listed.

SLIST list the observations SLIST

FUNCTION :

SLIST lists the pointing observations and the current residuals.

COMMAND :

SLIST   *r* *p*

where *r* is the report threshold, the minimum radial error below which an observation is not listed (in arcseconds, default zero), and *p* is the character P, used to split the report into screenfuls (default non-paged output).

NOTES :

The SLIST output includes the residuals in various directions rather than simply in radius.

If only the RMS residuals are needed the command `'REPLEN S'` may be used to suppress reporting the individual observations.

The usual value for r is the default zero, so that all stars are listed (always depending on the report-length option, controlled by the REPLEN command).

MASKed stars are regarded as having zero radial error, so that they never appear in the listing for non-zero r.

The azimuths are reckoned from north through east.

If both arguments are used (specifying paged output as well as a radial-error threshold) it doesn't matter whether the P character comes first or second.

Subset membership is indicated on the listing by the inclusion of the equivalent INDAT D-records. This feature is suppressed when a non-zero threshold has been specified.

SLIST is used to display the observations on the screen. Where output to a file is required, for further processing outside TPOINT, the FLIST command can be used instead.

SPAWN   execute a Unix shell command   **SPAWN**

FUNCTION :

SPAWN executes one or more C-shell commands.

COMMAND :

> SPAWN *string*

where *string* is the required shell command, and consists of either the whole of the TPOINT command line following the `'SPAWN'` name but with leading and trailing blanks eliminated or, if the first non-space character following the command name is a `'` or `"` delimiter, the string between that delimiter and the next appearance of the same one (unless the end of the command is reached first).

NOTE :

If no argument is supplied a new shell is spawned, allowing a sequence of commands then to be entered. To return to TPOINT, issue an `exit` command.

SUBSET   assign subset membership   SUBSET

FUNCTION :

SUBSET assigns all MASKed observations to a specified data subset.

COMMAND :

> SUBSET *subset*

where *subset* is the name of the data subset.

NOTES :

If the subset name is present, MASKed observations become members of the named subset in addition to any previous subset membership.

If the subset name is absent, MASKed observations lose all pre-existing subset membership.

The command cannot be used to cancel membership of an individual subset in a single call. Either (i) membership of all subsets is cancelled, or (ii) the observation becomes a member of a new subset while retaining previous memberships. Cancelling membership of an individual subset would require operation (i) followed by repeated applications of (ii) to make good the unwanted cancellations.

MASKed observations remain MASKed on completion. To bring the observations into use will require appropriate UNMASK operations.

In error cases, the data list remains intact but in the state reached immediately before the error occurred.

UNFIT   apply model in reverse   UNFIT

FUNCTION :

UNFIT applies a pointing model in reverse, taking the current adjusted positions and predicting the observations that produce those adjusted positions when the model is applied.

COMMAND :

> UNFIT   to apply the current model
> or   UNFIT N   to apply a null model (coeffs all zero)

NOTES :

> If the star-to-telescope modeling option has been chosen, (via the ADJUST command) the star positions are set and the telescope positions left alone. If the telescope-to-star option has been chosen, the reverse is true.

> A common use for the UNFIT command is where an adopted standard model is applied to a set of pointing residuals to yield "observations" which can be combined for further analysis.

> For further details, see Section 5.5.

UNMARK   reverse earlier MARK commands   **UNMARK**

FUNCTION :

> Reverse earlier MARK commands: set all MARKed observations back to the default plotting pen (or to a nominated different one) and reMASK them.

COMMAND :

> UNMARK n

> where n is the pen number.

NOTES :

> The default is the pen used for normal points.

> The actual colors are dependent on the implementation of the TPOINT graphics subsystem being used. The current selections can be inspected by executing the command PENS.

UNMASK   flag selected observations active   **UNMASK**

FUNCTION :

> UNMASK flags selected pointing observations active. The selection is made by area of sky, total residual, or sequence number.

> MASK/UNMASK can also be used to mark out selected observations temporarily for various purposes, such as assigning them to a specified data subset (via the SUBSET command) or plotting them in a different color (via the MARK command).

COMMAND :

> UNMASK *quantity condition value*
> or   UNMASK *n1 n2*

where the arguments are as follows:

quantity	H (HA), D (Dec), A (Az), Z (ZD), E (El)	
	R (radial error) or N (observation number)	
condition	L (less than) or G (greater than)	
value	cutoff value (hours for H, degrees for D, A, Z or E,	
	arcseconds for R, number for N)	

or	*n1*	first observation number
	n2	last observation number (defaults to *n1*)

NOTES :

If the arguments are omitted, all observations are UNMASKed.

The inverse command is MASK.

Azimuths lie within the range 0 to 360°, reckoned from north through east.

Observation numbers:

- start at 1 and refer to all observations, whether or not currently active;
- can be given in either order;

EXAMPLES :

UNMASK H L 4	makes active all observations where hour angle is less than 4^h (60°)
UNMASK Z G 20	makes active all observations where zenith distance is greater than 20°
UNMASK N G 20	makes active all but the first 20 observations
UNMASK 3	makes active the 3rd observation
UNMASK 1 25	makes active the first 25 observations
UNMASK	makes all the observations active

USE   include terms in model   USE

FUNCTION :

USE includes one or more terms in the pointing model, and flags it or them to be fitted.

COMMAND :

USE *coeff1 coeff2* etc.

where the arguments are the names of the terms to be included in the model.

NOTES :

Any term already in the model is flagged to be fitted; in this case USE cancels a prior FIX.

If no arguments are supplied, all terms currently in the model are flagged to be fitted.

If any argument is unrecognized, the entire command is rejected.

VT   clear the text screen   **VT**

FUNCTION :

VT declares the text screen VT100-compatible, selects the scrolling region and clears the screen.

COMMAND :

        VT *top bottom* (declares ANSI and specifies scroll)
  or VT N (declares non-ANSI)

NOTES :

1. The scrolling region extends from line *top* to line *bottom* inclusive. On a VT100-compatible screen, the top line is line 1, and the bottom line is line 24. The specified region must be at least two lines in extent.

2. The default values are 24 for *bottom* and 1 for *top*. Thus if only the first argument is given the scrolling region extends down to the bottom of the screen, and if no arguments are given the whole screen is used.

3. The screen is cleared each time this command is used, unless the "N" option is specified. The VT command without arguments is thus a useful way of decluttering the screen on certain older types of terminal which have independent but superimposed graphics and alpha planes.

4. The effect of using this command to declare that the terminal is ANSI cannot be predicted on non-ANSI terminals.

7.2 Pointing terms: names and sign conventions

This section contains a description and a formula for every TPOINT pointing term; the list is in alphabetical order.

The formulas are an essential resource for anyone wishing to write telescope control software incorporating TPOINT corrections. However, note that for clarity they are given in the simplest form possible, usually as spherical trigonometry expressions, and it may not be enough simply to code them into BASIC, FORTRAN, C etc. as they stand: it is up to the programmer to attend to such details as numerical precision, wrap-around and the avoidance of computational problems in awkward cases such as close to zenith, pole and horizon.

In addition, the programmer is responsible for providing the transformation from catalog mean place into the "observed" place which is the starting-point for TPOINT corrections. Starting from J2000 mean $[\alpha, \delta]$, the sequence of operations involved in this transformation is shown diagramatically in Figure 1.

The pointing term formulas obey the following nomenclature and sign conventions:

ANGLES

- **hour angle**: h is positive west of the meridian.

- **declination**: δ is positive north of the equator.

- **parallactic angle**: q is positive west of the meridian.

- **azimuth**: for most TPOINT purposes, A is zero for due north, and $90°$ for due east.[10]

- **zenith distance**: the zenith is at $\zeta = 0°$.

- **elevation**: $E = 90° - \zeta$.

- **latitude**: the site geodetic latitude, ϕ, is positive in the northern hemisphere.

CORRECTIONS

- **hour angle and east-west corrections**: Δh and ΔX ($\simeq \Delta h \cos \delta$) are positive when the corrected telescope position is west of the uncorrected position. Examples: IH, NP, CH.

---

[10]This is true for the INDAT input file, the SLIST report and the pointing-term formulas given later. However, internally A is zero for due south, and $90°$ for due east. The only place where this internal convention comes to the surface is in the polynomial, harmonic and auxiliary-reading pointing terms. To re-express these terms in the north-through-east convention, flip the sign of ΔA and flip any term involving $\cos A, \sin 2A, \cos 3A$ etc.

mean $[\alpha, \delta]$, epoch & equinox J2000

space motion

mean $[\alpha, \delta]$, equinox J2000, current epoch

annual parallax
light deflection
annual aberration
precession-nutation

Apparent $[\alpha, \delta]$

Earth rotation

Apparent $[h, \delta]$

diurnal aberration

Topocentric $[h, \delta]$

$[h, \delta]$ to $[Az, El]$

Topocentric $[Az, El]$

refraction

Observed Place
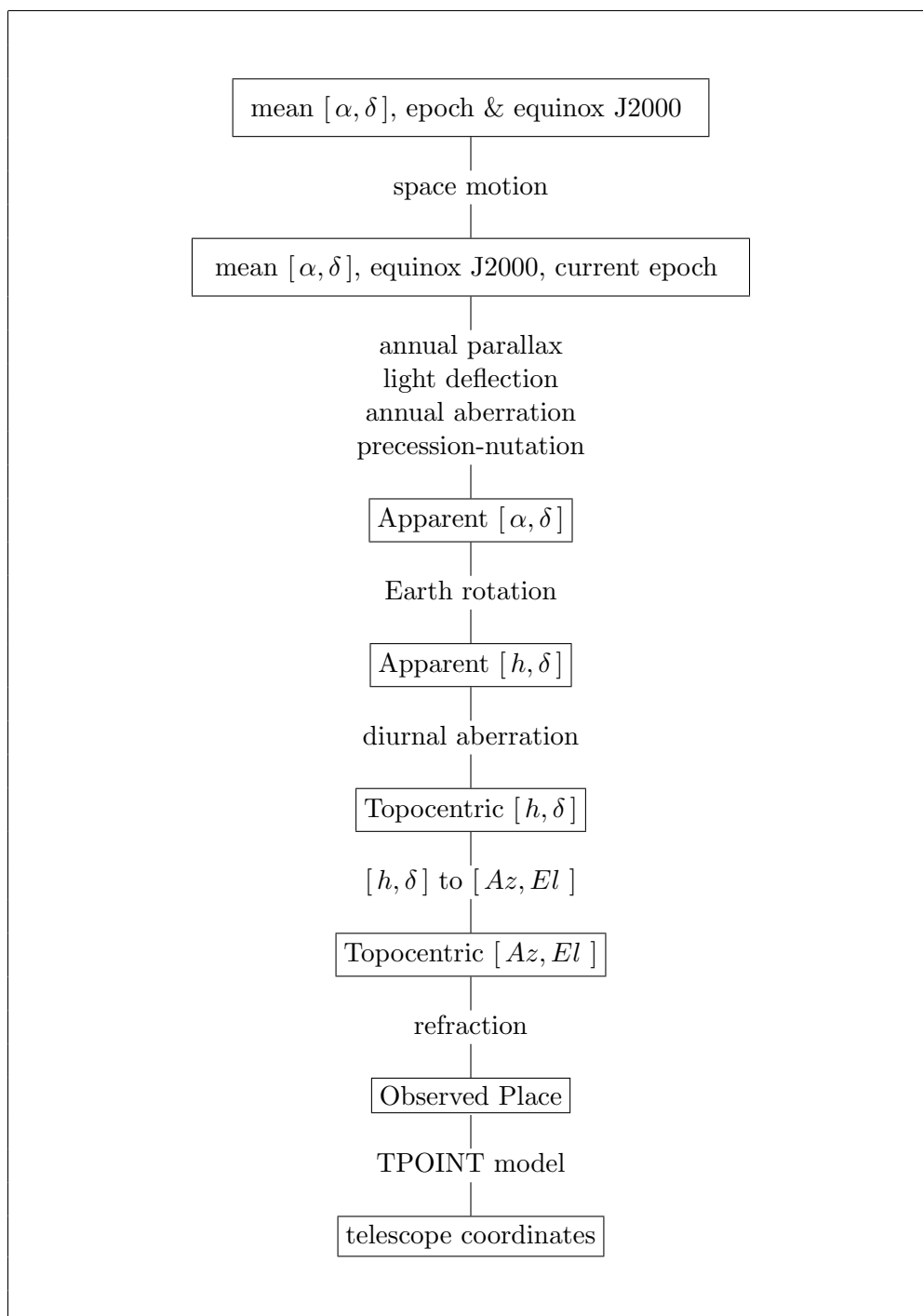
TPOINT model

telescope coordinates

Figure 8: The TPOINT corrections are just part of the sequence of transformations and corrections needed to bridge the gap between (i) the catalog $[\alpha, \delta]$ of the star and (ii) where the telescope is told to point in order to acquire the star. It is the responsibility of the telescope control system to provide the astrometric transformations that go from catalog coordinates all the way to "observed place", after which the TPOINT model takes over. (In the diagram, parallax, light deflection and diurnal aberration are included for completeness but are negligible for most practical purposes related to TPOINT.)

- **declination corrections**: $\Delta\delta$ is positive when the corrected telescope position is north of the uncorrected position. Example: ID.

- **azimuth and left-right corrections**: ΔA and ΔS ($\simeq \Delta A \cos E$) are positive when the corrected telescope position is to the left of the uncorrected position as seen by someone standing at the telescope looking at the sky. Examples: IA, NPAE, CA.

- **elevation corrections**: ΔE is positive when the corrected telescope position is above the uncorrected position. Example: IE.

- **Cartesian corrections**: Δx, Δy, Δz are positive when the corrections increase x, y, z. (All TPOINT $[\,x, y, z\,]$ systems are right-handed; the z-axis is the positive pole, and the x-axis points to zero longitude.)

The terms are reversed in sign when adjusting star positions to fit telescope positions (as selected via the ADJUST command), so that the coefficients stay unchanged in sign whichever of the two options (star adjusted to fit telescope, or telescope adjusted to fit star) is being used.

Note that the "corrections" act in the sense that they add to an imperfect encoder reading to produce an improved estimate of the true pointing. The TPOINT model corrects the imperfect readouts, and to calculate what encoder readings to command in order to achieve correct pointing, the TPOINT model must be **subtracted** from the ideal values. In other words:

- To improve imperfect encoder readings, **ADD** the TPOINT corrections.

- To point correctly, **SUBTRACT** the TPOINT corrections from the desired pointing before commanding the mount.

Further complications naturally arise where the encoders themselves do not follow the assumed sign conventions, for example if the vertical readout of an altazimuth mount increases with zenith distance rather than elevation. The final interpretation should always be verified by performing a "dummy" pointing test – see Section 4.10.

---

polynomial   polynomial   *polynomial*

DESCRIPTION :

Generic terms with names that start with the letter 'P' are simple polynomials, which apply adjustments to a *result* coordinate which are proportional to the product of two *input* coordinates each of which is raised to an integer *power*. As a rule, such terms are used empirically, but in some cases there may be a simple mechanical interpretation, for example a scaling error.

SYNTAX :

Polynomial terms have names of the form:

Prc [i [c [i]]]

The initial 'P' flags this term as a polynomial.

The r field describes the result, and is one of the following:

H	result is in hour angle
X	result is east-west
D	result is in declination
U	result tilts north polar axis up/down
L	result tilts polar axis left/right
P	result changes HA/Dec nonperpendicularity
A	result is in azimuth (*n.b.* south = 0°, east = 90°)
S	result is left-right
Z	result is in zenith distance (sky)
E	result is in elevation (mount)
N	result tilts azimuth axis north/south
W	result tilts azimuth axis east/west
V	result changes Az/El nonperpendicularity

The two ci fields indicate the independent variables and their powers. Each i is in the range 0–9; each c can be any of:

H	hour angle
D	declination
A	azimuth (*n.b.* south = 0°, east = 90°)
Z	zenith distance (sky)
E	elevation (mount)
Q	parallactic angle

expressed in radians. Trailing ci or i fields, if omitted, default to unity. For example, a change in hour angle proportional to hour angle (i.e. a scale change, such as might be necessary with a roller-driven encoder) can be produced by using the term PHH.

The same independent variable can be specified twice, allowing powers up to 18 to be used.

FORMULA :

The general scheme is as described above. To take a specific example, PSA1E2 is a polynomial (P) which models an effect which produces a leftwards shift (S) proportional to $A \cdot E^2$ (A1E2):

$$\Delta S = + \texttt{PSA1E2} \; A \; E^2$$

A and E are in radians.

NOTES :

Polynomials are very powerful and general, but when $i > 1$ are apt to behave badly outside the area covered by pointing observations. They can be useful for attacking specific irregularities and flexures which gentler, trigonometry-based, terms are too smooth to attack. When using polynomials in this way, it is wise to FIX the "theoretical" model, except for zero-point terms (IH, ID, CH, IA, IE, CA), allowing the polynomial access only to the residual errors.

Note that polynomials are sensitive to "wrap": azimuth 10° and azimuth 370° are **not** the same thing to a polynomial (unlike a trigonometrical term).

---

harmonic	harmonic	*harmonic*

DESCRIPTION :

Generic terms with names that start with the letter 'H' are harmonics, which apply adjustments to a *result* coordinate which are proportional to the sine or cosine of one *input* coordinate with the sine or cosine of another. As a rule, such terms are used empirically, after inspection of the plots produced by the G command, and perhaps guided by the H and H2 commands, but in many cases there may be a plausible mechanical interpretation. Indeed, most of the non-empirical terms can be "spelt out" as harmonics.

SYNTAX :

Harmonic terms have names of the forms:

> H *r f c* [*i*] [*f c* [*i*]]
> or   H *r f c* [*i* [*i* [*i*]]]

The initial 'H' flags this term as a harmonic.

The *r* field describes the result, and is one of the following:

H	result is in hour angle
X	result is east-west
D	result is in declination
U	result tilts polar axis up/down
L	result tilts polar axis left/right
P	result changes HA/Dec nonperpendicularity
A	result is in azimuth (*n.b.* south = 0°, east = 90°)
S	result is left-right
Z	result is in zenith distance (sky)
E	result is in elevation (mount)
N	result tilts azimuth axis north/south
W	result tilts azimuth axis east/west
V	result changes Az/El nonperpendicularity

Each *fci*, *fcii* and *fciii* field indicates a function of an integer multiple of an independent variable *c*, one of:

H	hour angle
D	declination
A	azimuth (*n.b.* south = 0°, east = 90°)
Z	zenith distance (sky)
E	elevation (mount)
Q	parallactic angle

The *f* field is either S for sine or C for cosine. Each *i* is in the range 0–9, allowing frequencies from zero to 999 cycles per revolution in the case of simple one-coordinate harmonics, and 0 to 9 cycles per revolution in the case of compound two-coordinate harmonics. An omitted *i* defaults to unity, as does an omitted trailing *fci*.

FORMULA :

The general scheme is as described above. To take a specific example, the term HXCH2SD would model an effect which produced an east-west shift (X) proportional to cosine (C) of $2h$ (H2) times sine (S) of δ (D):

$$\Delta X = + \texttt{HXCH2SD} \ \cos 2h \sin \delta$$

NOTES :

Harmonics, like polynomials, are a very powerful way of treating pointing errors empirically, but are less likely to diverge outside the area covered by pointing observations. It is usually advisable to FIX the "theoretical" model, except for zero-point terms (IH, ID, CH, IA, IE, CA), before using a set of harmonic terms to tackle the residual errors.

As noted earlier, it is possible to build most of the theoretical terms by using harmonics (though there is a small speed advantage in using the "named" term). For example, to model fork flexure in an equatorial mount the terms FO and HDCH are identical. However, where a single mechanical error affects both coordinates (for example polar axis elevation error), using two separate harmonics would not be the same as the single theoretical term because the two coefficients would not be constrained to be identical.

---

auxiliary   auxiliary   *auxiliary*

DESCRIPTION :

Generic terms with names that start with the letter $'\texttt{A}'$ are auxiliaries, which apply adjustments to a *result* coordinate which are proportional to one of the auxiliary readings.

SYNTAX :

Auxiliary terms have names of the forms:

A *n r*

The initial $'$A$'$ flags this term as an auxiliary.

The decimal number *n* is in the range 1–99, and specifies which auxiliary reading is to be used.

The *r* field describes the result, and is one of the following:

H	result is in hour angle
X	result is east-west
D	result is in declination
U	result tilts polar axis up/down
L	result tilts polar axis left/right
P	result changes HA/Dec nonperpendicularity
A	result is in azimuth (*n.b.* south = 0°, east = 90°)
S	result is left-right
Z	result is in zenith distance (sky)
E	result is in elevation (mount)
N	result tilts azimuth axis north/south
W	result tilts azimuth axis east/west
V	result changes Az/El nonperpendicularity

NOTES :

Auxiliary readings may be appended to the records input by the INDAT command, one or two per star (or up to 99 if separated from the mandatory part of the record by an ampersand character $'$&$'$). Common uses are (i) measurements made by sensors placed on the telescope and (ii) raw encoder readings. Mechanical displacements and temperature gradients are examples of the type of measurement which might be made. Raw encoder readings are required for cases of scale error (it is usually impossible to use the encoded coordinate directly because the latter has undergone normalization into a specific range). For example, a good way of determining azimuth encoder is to repeat the encoder azimuth as the final field of each observation and to use the term A1A. (*n.b.* It is advisable to express the reading in radians or turns rather than degrees in order to avoid inconveniently small coefficient values.)

In cases where a single coefficient is to be fitted that has a vector outcome, a variant called a "vector auxiliary" can be used:

A *n1 r1 n2 r2*

The two auxiliary readings are specified by *n1* and *n2*, and the two results are *r1* and *r2*. For example, if basis function values for corrections in hour angle and declination have been supplied as auxiliary readings #13 and #5, the single term A13H5D would be used. If separate A13H and A5D terms are used instead, a fit would probably yield two approximately equal coefficients, but they would not be constrained to be equal.

ACEC   azimuth centering error, cosine component   ACEC

DESCRIPTION :

The cosine component of the once-per-revolution cyclic errors produced by a mis-centered azimuth setting-circle.

FORMULA :

$$\Delta A = +\ \texttt{ACEC}\ \cos A$$

(The azimuth sign convention is that $A = 0°$ is north and $A = 90°$ is east.)

NOTES :

The sine component is the term ACES.

ACES   azimuth centering error, sine component   ACES

DESCRIPTION :

The sine component of the once-per-revolution cyclic errors produced by a mis-centered azimuth setting-circle.

FORMULA :

$$\Delta A = -\ \texttt{ACES}\ \sin A$$

(The azimuth sign convention is that $A = 0°$ is north and $A = 90°$ is east.)

NOTES :

The cosine component is the term ACEC.

AN   azimuth axis misalignment NS   AN

DESCRIPTION :

In an altazimuth mount, misalignment of the azimuth axis north-south: rotation about a horizontal east-west axis equal to coefficient AN.

FORMULA :

$$\Delta A \simeq - \texttt{AN} \sin A \tan E$$

$$\Delta E \simeq - \texttt{AN} \cos A$$

(The azimuth sign convention is that $A = 0°$ is north and $A = 90°$ is east.)

NOTES :

AN is one of the six purely geometrical terms that affect all altazimuth mounts, the others being IA, IE, CA, NPAE and AW.

If AN is positive, the pole of the mounting is north of the zenith.

The other (i.e. east-west) component of the azimuth axis misalignment is the term AW.

The approximate formulas given above are implemented literally in the term ANL.

AUX1A azimuth adjustment from Aux. 1 AUX1A

DESCRIPTION :

Change in azimuth equal to coefficient AUX1A multiplied by the first auxiliary reading.

FORMULA :

$$\Delta A = - \texttt{AUX1H} \cdot \text{aux}_1$$

(The azimuth sign convention is that $A = 0°$ is north and $A = 90°$ is east.)

AUX1D δ adjustment from Aux. 1 AUX1D

DESCRIPTION :

Change in declination equal to coefficient AUX1D multiplied by the first auxiliary reading.

FORMULA :

$$\Delta \delta = + \texttt{AUX1D} \cdot \text{aux}_1$$

AUX1E   elevation adjustment from Aux. 1   **AUX1E**

DESCRIPTION :

Elevation change equal to coefficient AUX1E multiplied by the first auxiliary reading.

FORMULA :

$$\Delta E = +\ \texttt{AUX1E} \cdot \mathrm{aux}_1$$

AUX1H   H.A. adjustment from Aux. 1   **AUX1H**

DESCRIPTION :

Change in hour angle equal to coefficient AUX1H multiplied by the first auxiliary reading.

FORMULA :

$$\Delta h = +\ \texttt{AUX1H} \cdot \mathrm{aux}_1$$

AUX1S   horizontal adjustment from Aux. 1   **AUX1S**

DESCRIPTION :

Change left-right equal to coefficient AUX1S multiplied by the first auxiliary reading.

FORMULA :

$$\Delta A \simeq -\ \texttt{AUX1S} \cdot \mathrm{aux}_1 \cdot \sec E$$

(The azimuth sign convention is that $A = 0°$ is north and $A = 90°$ is east.)

AUX1X   EW adjustment from Aux. 1   **AUX1X**

DESCRIPTION :

Change east-west equal to coefficient AUX1X multiplied by the first auxiliary reading.

FORMULA :

$$\Delta h \simeq +\ \texttt{AUX1X} \cdot \mathrm{aux}_1 \cdot \sec \delta$$

AUX2A   azimuth adjustment from Aux. 2   AUX2A

DESCRIPTION :

Change in azimuth equal to coefficient AUX2A multiplied by the second auxiliary reading.

FORMULA :

$$\Delta A = - \; \texttt{AUX2H} \cdot \mathrm{aux}_2$$

(The azimuth sign convention is that $A = 0°$ is north and $A = 90°$ is east.)

AUX2D δ adjustment from Aux. 2   AUX2D

DESCRIPTION :

Change in declination equal to coefficient AUX2D multiplied by the second auxiliary reading.

FORMULA :

$$\Delta \delta = + \; \texttt{AUX2D} \cdot \mathrm{aux}_2$$

AUX2E   elevation adjustment from Aux. 2   AUX2E

DESCRIPTION :

Elevation change equal to coefficient AUX2E multiplied by the second auxiliary reading.

FORMULA :

$$\Delta E = + \; \texttt{AUX2E} \cdot \mathrm{aux}_2$$

AUX2H   H.A. adjustment from Aux. 2   AUX2H

DESCRIPTION :

Change in hour angle equal to coefficient AUX2H multiplied by the second auxiliary reading.

FORMULA :

$$\Delta h = + \; \texttt{AUX2H} \cdot \mathrm{aux}_2$$

AUX2S   horizontal adjustment from Aux. 2   **AUX2S**

DESCRIPTION :

Change left-right equal to coefficient AUX2S multiplied by the second auxiliary reading.

FORMULA :

$$\Delta A \simeq - \texttt{AUX2S} \cdot \mathrm{aux}_2 \cdot \sec E$$

(The azimuth sign convention is that $A = 0°$ is north and $A = 90°$ is east.)

AUX2X   EW adjustment from Aux. 2   **AUX2X**

DESCRIPTION :

Change east-west equal to coefficient AUX2X multiplied by the second auxiliary reading.

FORMULA :

$$\Delta h \simeq + \texttt{AUX2X} \cdot \mathrm{aux}_2 \cdot \sec \delta$$

AW   azimuth axis misalignment EW   **AW**

DESCRIPTION :

In an altazimuth mount, misalignment of the azimuth axis east-west: rotation about a horizontal north-south axis equal to coefficient AW.

FORMULA :

$$\Delta A \simeq - \texttt{AW} \ \cos A \ \tan E$$

$$\Delta E \simeq + \texttt{AW} \ \sin A$$

(The azimuth sign convention is that $A = 0°$ is north and $A = 90°$ is east.)

NOTES :

AW is one of the six purely geometrical terms that affect all altazimuth mounts, the others being IA, IE, CA, NPAE and AN.

If AW is positive, the pole of the mounting is west of the zenith.

The other (i.e. north-south) component of the azimuth axis misalignment is the term AN.

The approximate formulas given above are implemented literally in the term AWL.

AWGS   Gemini S azimuth axis misalignment EW   **AWGS**

DESCRIPTION :

A distorted form of the AW term (misalignment of the azimuth axis east-west) that is peculiar to Gemini South. It is a rotation about a horizontal NS axis equal to coefficient AWGS but with an empirically determined adjustment to the az/el nonperpendicularity component.

FORMULA :

$$\Delta A \simeq - \text{ AWGS } \cos A \tan E \cdot f$$

$$\Delta E \simeq + \text{ AWGS } \sin A$$

where $f = 2.187 - (1.68 \times 10^{-4} - 5.9 \times 10^7 \cdot \text{AWGS}) \cdot \text{AWGS}$.

(The azimuth sign convention is that $A = 0°$ is north and $A = 90°$ is east.)

NOTES :

If AWGS is positive, the pole of the mounting is west of the zenith.

For Gemini South, the adjustment factor f is typically somewhat less than unity, reaching unity at $\text{AWGS} = 26\rlap{.}''8$.

CA   LR collimation error   **CA**

DESCRIPTION :

In an altazimuth mount, the collimation error is the non-perpendicularity between the nominated pointing direction and the elevation axis. It produces a left-right shift on the sky that is constant for all elevations.

FORMULA :

$$\Delta A \simeq - \text{ CA } \sec E$$

(The azimuth sign convention is that $A = 0°$ is north and $A = 90°$ is east.)

NOTES :

CA is one of the six purely geometrical terms that affect all altazimuth mounts, the others being IA, IE, NPAE, AN and AW.

A non-zero CA on its own means there is an area around the zenith inside which the telescope cannot point. (This is a geometrical limitation and is distinct from the blind spot caused by velocity and acceleration limits close to the zenith.)

Collimation error has many causes – misalignment of the optics, an inaccurately centered eyepiece graticule and so on.

The approximate formula given above is implemented literally in the term CAL.

CD4A   AAT coudé 4 collimation A component   CD4A

DESCRIPTION :

AAT coudé 4 collimation error, A-component: a change in hour angle equal to coefficient CD4A, and a change in declination equal to the same coefficient multiplied by $\sin \delta$.

FORMULA :

$$\Delta h = +\ \texttt{CD4A}$$

$$\Delta \delta = +\ \texttt{CD4A}\ \sin \delta$$

NOTES :

There are many variants of the coudé optical configuration, and the above AAT term may not be applicable to other telescopes.

CD4B   AAT coudé 4 collimation B component   CD4B

DESCRIPTION :

AAT coudé 4 collimation error, B-component: a change east-west equal to coefficient CD4B multiplied by $-\sin \delta$, and a change in δ equal to the same coefficient multiplied by $\cos \delta$.

FORMULA :

$$\Delta h \simeq -\ \texttt{CD4B}\ \tan \delta$$

$$\Delta \delta = +\ \texttt{CD4B}\ \cos \delta$$

NOTES :

There are many variants of the coudé optical configuration, and the above AAT term may not be applicable to other telescopes.

CD5A   AAT coudé 5 collimation A component   CD5A

DESCRIPTION :

AAT coudé 5 collimation error, A-component: a change east-west equal to coefficient CD5A multiplied by $-\sin(h + \delta)$, and a change in δ equal to the same coefficient multiplied by $\cos(h + \delta)$.

FORMULA :

$$\Delta h \simeq -\ \texttt{CD5A}\ \sin(h + \delta)\ \sec\delta$$

$$\Delta\delta = +\ \texttt{CD5A}\ \cos(h + \delta)$$

NOTES :

There are many variants of the coudé optical configuration, and the above AAT term is unlikely to be applicable to other telescopes.

CD5B   AAT coudé 5 collimation B component   CD5B

DESCRIPTION :

AAT coudé 5 collimation error, B-component: a change east-west equal to coefficient CD5B multiplied by $\cos(h + \delta)$, and a change in δ equal to the same coefficient multiplied by $\sin(h + \delta)$.

FORMULA :

$$\Delta h \simeq -\ \texttt{CD5B}\ \cos(h + \delta)\ \sec\delta$$

$$\Delta\delta = +\ \texttt{CD5B}\ \sin(h + \delta)$$

NOTES :

There are many variants of the coudé optical configuration, and the above AAT term is unlikely to be applicable to other telescopes.

CH   EW collimation error   **CH**

DESCRIPTION :

In an equatorial mount, the collimation error is the non-perpendicularity between the nominated pointing direction and the declination axis. It produces an east-west shift that is constant for all declinations.

FORMULA :

$$\Delta h \simeq + \; \text{CH} \; \sec \delta$$

NOTES :

CH is one of the six purely geometrical terms that affect all equatorial mounts, the others being IH, ID, NP, ME and MA.

A non-zero CH on its own means there is an area around the pole inside which the telescope cannot point.

Collimation error has many causes – misalignment of the optics, an inaccurately centered eyepiece graticule, a skewed dovetail assembly, and so on.

The approximate formula given above is implemented literally in the term CHL.

CRX   altaz coudé displacement, NS   **CRX**

DESCRIPTION :

In an altazimuth mount, optical components fixed to the stationary pier in a coudé configuration will in general not be perfectly aligned with respect to the azimuth axis. The CRX term allows for the north-south component of such a displacement. The displacement produces an pointing shift on the sky with a horizontal component proportional to the cosine of azimuth plus elevation and a vertical component proportional to minus the sine of the same angle.

FORMULA :

$$\Delta A \simeq + \; \text{CRX} \; \cos(A - E) \sec E$$

$$\Delta E \simeq - \; \text{CRX} \; \sin(A - E)$$

(The azimuth sign convention is that $A = 0°$ is north and $A = 90°$ is east.)

NOTE :

The east-west component is the term CRY.

CRY   altaz coudé displacement, EW   **CRY**

DESCRIPTION :

In an altazimuth mount, optical components fixed to the stationary pier in a coudé configuration will in general not be perfectly aligned with respect to the azimuth axis. The CRY term allows for the east-west component of such a displacement. The displacement produces an pointing shift on the sky with a horizontal component proportional to the sine of azimuth plus elevation and a vertical component proportional to the cosine of the same angle.

FORMULA :

$$\Delta A \simeq -\ \texttt{CRY}\ \sin(A - E)\ \sec E$$

$$\Delta E \simeq -\ \texttt{CRY}\ \cos(A - E)$$

(The azimuth sign convention is that $A = 0°$ is north and $A = 90°$ is east.)

NOTE :

The north-south component is the term CRX.

DAB   declination axis bending   **DAF**

DESCRIPTION :

Downward bending of cantilevered declination axis (e.g. English cross-axis and German equatorial mountings) proportional to the sine of the zenith distance of the declination axis. To a good approximation, this manifests itself as an east-west shift that is proportional to the amount of bending times the cosine of the telescope zenith distance.

FORMULA :

$$\Delta h \simeq -\ \texttt{DAB}\ (\sin^2 h \sin^2 \phi + \cos^2 h)(\sin \phi \tan \delta + \cos \phi \cos h)$$

NOTES :

The convention for "downward" is such that the declination axis is assumed to emerge from the polar axis towards the west when the telescope points at the meridian.

The term DAF is similar but allows for "flop" (a displacement that does not vary as the mount rotates about the polar axis) rather than flexure (a displacement that *does* vary), which the present term models.

DAF   declination axis flop   **DAF**

DESCRIPTION :

Fixed downward "flop" of cantilevered declination axis (e.g. English cross-axis and German equatorial mountings). To a good approximation, this manifests itself an east-west shift that is proportional to the cosine of the telescope zenith distance.

FORMULA :

$$\Delta h \simeq - \text{ DAF } (\sin\phi\tan\delta + \cos\phi\cos h)$$

NOTES :

The convention for "downward" is such that the declination axis is assumed to emerge from the polar axis towards the west when the telescope points at the meridian.

The term DAB is similar but allows for flexure (a displacement that varies as the mount rotates about the polar axis) rather than flop.

DCEC δ centering error, cosine component   **DCEC**

DESCRIPTION :

The cosine component of the once-per-revolution cyclic errors produced by a miscentered declination setting-circle.

FORMULA :

$$\Delta\delta = + \text{ DCEC }\cos\delta$$

NOTES :

The sine component is the term DCES.

DCES δ centering error, sine component   **DCES**

DESCRIPTION :

The sine component of the once-per-revolution cyclic errors produced by a miscentered declination setting-circle.

FORMULA :

$$\Delta\delta = + \text{ DCES }\sin\delta$$

NOTES :

The cosine component is the term DCEC.

DGEC   AAT 9° δ gear error, cosine Term   **DGEC**

DESCRIPTION :

The AAT declination encoder pinion is geared 40:1 with respect to the declination, corresponding to 9°. The term DGEC is the cosine component of a cyclic error of this frequency.

FORMULA :

$$\Delta\delta = +\ \texttt{DGEC}\ \cos 40\delta$$

NOTES :

The corresponding sine term is DGES.

The AAT's 9° gear errors are at the upper end of the frequency range which is amenable to analysis through pointing tests, unless extremely dense sets of stars are used.

DGES   AAT 9° δ gear error, sine term   **DGES**

DESCRIPTION :

The AAT declination encoder pinion is geared 40:1 with respect to the declination, corresponding to 9°. The term DGES is the sine component of a cyclic error of this frequency.

FORMULA :

$$\Delta\delta = +\ \texttt{DGES}\ \sin 40\delta$$

NOTES :

The corresponding cosine term is DGEC.

The AAT's 9° gear errors are at the upper end of the frequency range which is amenable to analysis through pointing tests, unless extremely dense sets of stars are used.

DNP   dynamic h/δ nonperpendicularity   DNP

DESCRIPTION :

For an equatorial mount, a change in the h/δ nonperpendicularity proportional to $\sin h$.

FORMULA :

$$\Delta h \simeq + \mathtt{DNP} \ \sin h \ \tan \delta$$

NOTES :

The static form is the term NP.

ECEC   elevation centering error, cosine Component   ECEC

DESCRIPTION :

The cosine component of the once-per-revolution cyclic errors produced by a miscentered elevation setting-circle.

FORMULA :

$$\Delta E = + \mathtt{ECEC} \ \cos E$$

NOTES :

The sine component is the term ECES.

ECES   elevation centering error, sine component   ECES

DESCRIPTION :

The sine component of the once-per-revolution cyclic errors produced by a miscentered elevation setting-circle.

FORMULA :

$$\Delta E = + \mathtt{ECES} \ \sin E$$

NOTES :

The cosine component is the term ECEC.

FLOP   vertical sag   FLOP

DESCRIPTION :

Constant vertical displacement.

FORMULA :

$$\Delta Z = + \ \texttt{FLOP}$$

NOTES :

This applies to equatorials (also generalized gimbal mounts) and is often caused by loose optics or problems with mirror support systems.

FO   fork flexure   FO

DESCRIPTION :

Flexure in an equatorial fork mounting: change in declination proportional to $\cos h$.

FORMULA :

$$\Delta \delta = + \ \texttt{FO} \ \cos h$$

NOTES :

This model of fork flexure is based in the idea that the flexure is at a maximum on the meridian, that it affects only declination, and that at $h = 6^{\mathrm{h}}$ the flexural displacement leaves the pointing direction unaffected. These assumptions are usually borne out well in practice.

HCEC   H.A. centering error, cosine component   HCEC

DESCRIPTION :

The cosine component of the once-per-revolution cyclic errors produced by a miscentered hour angle setting-circle.

FORMULA :

$$\Delta h = + \ \texttt{HCEC} \ \cos h$$

NOTES :

The sine component is the term HCES.

HCES   H.A. centering error, sine component   **HCES**

DESCRIPTION :

The sine component of the once-per-revolution cyclic errors produced by a mis-centered hour angle setting-circle.

FORMULA :

$$\Delta h = + \; \texttt{HCES} \; \sin h$$

NOTES :

The cosine component is the term HCEC.

HF   AAT horseshoe flexure   **HF**

DESCRIPTION :

HF is an effect peculiar to the AAT. As the horseshoe turns there are changes in the non-perpendicularity between the telescope and the declination axis, perhaps due to distortion in the center section induced by the weight of the upper horseshoe tine.

FORMULA :

$$\Delta h \simeq + \; \texttt{HF} \; \sec \delta$$

NOTES :

This and other AAT-specific terms are included in the TPOINT package as a demonstration of what is involved in getting the best possible pointing out of a large telescope.

The HF effect was observed in early AAT pointing tests and had been predicted by structural analysis carried out prior to construction. It reaches about $20''$ in size.

HFD   AAT horseshoe flexure, NS   HFD

DESCRIPTION :

This term is one component of a complicated flexure model for the AAT's horse-shoe and yoke. It produces a north-south adjustment equal to the coefficient HFD multiplied by a canonical expression in hour angle and declination.

FORMULA :

$$
\begin{aligned}
\Delta\delta \;\; = \;\; & -2.529\sin 2h + 3.964\sin 3h + 3.008\cos 3h - 2.428\sin 4h \\
& -0.921\cos 5h - 0.233\cos 12h + 0.163\sin 6\delta \\
& -0.147\cos 11\delta - 0.244\cos 15h\sin\delta \\
& +(-4.330\cos h - 2.958\cos 2h - 1.805\sin h)\cos\delta \\
& +1.666\cos h\cos 2\delta
\end{aligned}
$$

NOTES :

The coefficient HFD is nominally unity (with the above coefficients in arcseconds).

This and other AAT-specific terms are included in the TPOINT package as a demonstration of what is involved in getting the best possible pointing out of a large telescope. This particular term, along with the east-west component HFX, was obtained by fitting empirical harmonics to the $\Delta\delta$ residuals left after a conventional model had been devised. Its largest effects occur at extreme hour angles.

HFX   AAT horseshoe flexure, EW   HFX

DESCRIPTION :

This term is one component of a complicated flexure model for the AAT's horse-shoe and yoke. It produces an east-west adjustment equal to the coefficient HFX multiplied by a canonical expression in hour angle and declination.

FORMULA :

$$
\begin{aligned}
\Delta h \;\; \simeq \;\; & (0.219\sin 5h + 0.368\cos 6h + 0.195\sin 15h + (1.279\sin 2h \\
& -1.718\sin 4h + 1.202\cos 5h)\sin\delta - 1.928\sin 3h\cos\delta \\
& +(3.662\sin h + 0.381\cos 3h)\sin 2\delta - 1.156\sin 3h\cos 2\delta \\
& +(-0.633\sin 2h + 0.723\sin h)\sin 5\delta)\sec\delta
\end{aligned}
$$

NOTES :

The coefficient HFX is nominally unity (with the above coefficients in arcseconds).

This and other AAT-specific terms are included in the TPOINT package as a demonstration of what is involved in getting the best possible pointing out of a large telescope. This particular term, along with the north-south component HFD, was obtained by fitting empirical harmonics to the $\Delta h \cos \delta$ residuals left after a conventional model had been devised. Its largest effects occur at extreme hour angles.

HGEC   AAT 36$^{\mathrm{m}}$ H.A. gear error, cosine term   **HGEC**

DESCRIPTION :

The AAT hour angle encoder pinion is geared 40:1 with respect to the polar axis, corresponding to 36$^{\mathrm{m}}$. The term HGEC is the cosine component of a cyclic error of this frequency.

FORMULA :

$$\Delta h = + \ \texttt{HGEC} \ \cos 40h$$

NOTES :

The corresponding sine term is HGES.

The AAT's 36$^{\mathrm{m}}$ gear errors are at the upper end of the frequency range which is amenable to analysis through pointing tests (as opposed to tracking tests), unless extremely dense sets of stars are used.

HGES   AAT 36$^{\mathrm{m}}$ H.A. gear error, sine term   **HGES**

DESCRIPTION :

The AAT hour angle encoder pinion is geared 40:1 with respect to the polar axis, corresponding to 36$^{\mathrm{m}}$. The HGES is the sine component of a cyclic error of this frequency.

FORMULA :

$$\Delta h = + \ \texttt{HGES} \ \sin 40h$$

NOTES :

The AAT's 36$^{\mathrm{m}}$ gear errors are at the upper end of the frequency range which is amenable to analysis through pointing tests (as opposed to tracking tests), unless extremely dense sets of stars are used.

The corresponding cosine term is HGEC.

IA azimuth index error **IA**

DESCRIPTION :

Azimuth index error in an altazimuth mount: the zero-point error in A.

FORMULA :

$$\Delta A = - \; \texttt{IA}$$

(The azimuth sign convention is that $A = 0°$ is north and $A = 90°$ is east.)

NOTES :

On many altazimuth telescopes, IA is arbitrarily set at the start of each night by pointing at a calibration star, and on telescopes without absolute encoders or readouts there is no choice; under these circumstances the IA value returned by TPOINT has no lasting significance. However, note that it is not the same thing as a horizontal error, such as might be caused by a badly adjusted primary mirror; the latter, addressed by the CA term, would produce the same image displacement at all elevations, whereas IA has a lessening effect as the zenith is approached.

IA is one of the six purely geometrical terms that affect all altazimuth mounts, the others being IE, CA, NPAE, AN and AW.

ID declination index error **ID**

DESCRIPTION :

Declination index error in an equatorial mount: the zero-point error in δ.

FORMULA :

$$\Delta \delta = + \; \texttt{ID}$$

NOTES :

ID produces a fixed offset of the image north-south. On many telescopes it is arbitrarily set at the start of each night by pointing at a calibration star, and on telescopes without absolute encoders or readouts there is no choice; under these circumstances the ID value returned by TPOINT has no lasting significance. It is indistinguishable from various other north-south shifts, such as those caused by imperfect collimation.

ID is one of the six purely geometrical terms that affect all equatorial mounts, the others being IH, CH, NP, ME and MA.

IE   elevation index error   **IE**

DESCRIPTION :

Elevation index error in an altazimuth mount: the zero-point error in E.

FORMULA :

$$\Delta E = + \; \texttt{IE}$$

NOTES :

IE produces a fixed elevation offset of the image. On many altazimuth telescopes it is arbitrarily set at the start of each night by pointing at a calibration star, and on telescopes without absolute encoders or readouts there is no choice; under these circumstances the IE value returned by TPOINT has no lasting significance. Except for the generalized gimbal case, it is indistinguishable from various other vertical shifts, such as those caused by imperfect collimation.

IE is one of the six purely geometrical terms that affect all altazimuth mounts, the others being IA, CA, NPAE, AN and AW.

IH   hour angle index error   **IH**

DESCRIPTION :

Hour angle index error in an equatorial mount: the zero-point error in h.

FORMULA :

$$\Delta h = + \; \texttt{IH}$$

NOTES :

IH has the same effect on pointing as an error in the clock or using an inaccurate value for site longitude. On many telescopes it is arbitrarily set at the start of each night by pointing at a calibration star, and on telescopes without absolute encoders or readouts there is no choice; under these circumstances the IH value returned by TPOINT has no lasting significance. However, note that it is not the same thing as an east-west error, such as might be caused by a badly adjusted primary mirror; the latter, addressed by the CH term, would produce the same image displacement at all declinations, whereas IH has a lessening effect as the pole is approached.

IH is one of the six purely geometrical terms that affect all equatorial mounts, the others being ID, CH, NP, ME and MA.

MA   polar-axis misalignment LR   MA

DESCRIPTION :

Misalignment of the polar axis of an equatorial mount to the left or right of the true pole: a rotation about an axis through $(h = \delta = 0)$ equal to coefficient MA.

FORMULA :

$$\Delta h \simeq -\ \mathtt{MA}\ \cos h\ \tan \delta$$

$$\Delta \delta \simeq +\ \mathtt{MA}\ \sin h$$

NOTES :

In the northern hemisphere, positive MA means that the pole of the mounting is to the right of due north.

In the southern hemisphere, positive MA means that the pole of the mounting is to the right of due south.

To avoid unwanted field rotation effects it is best to eliminate MA mechanically by an appropriate azimuth adjustment. To eliminate MA arcseconds of polar axis azimuth error, rotate the mounting $\mathtt{MA} \sec \phi$ arcseconds anticlockwise as seen from above. (See Section 6).

The other (i.e. up-down) component of the polar axis misalignment is the term ME.

The approximate formulas given above are implemented literally in the term MAL.

ME   polar-axis misalignment in elevation   ME

DESCRIPTION :

Vertical misalignment of the polar axis of an equatorial mount: a rotation about an east-west axis equal to coefficient ME.

FORMULA :

$$\Delta h \simeq +\ \mathtt{ME}\ \sin h\ \tan \delta$$

$$\Delta \delta \simeq +\ \mathtt{ME}\ \cos h$$

NOTES :

In the northern hemisphere, positive ME means that the pole of the mounting is below the true (unrefracted) pole. A mounting aligned the refracted pole (for most telescopes probably the simplest and best thing to aim for in order to avoid unwanted field rotation effects – see Section 6) will have negative ME.

In the southern hemisphere, positive ME means that the pole of the mounting is above the true (unrefracted) pole, and a mounting aligned the refracted pole will have positive ME.

The other (i.e. left-right) component of the polar axis misalignment is the term MA.

The approximate formulas given above are implemented literally in the term MEL.

NP   H.A./dec non-perpendicularity   NP

DESCRIPTION :

In an equatorial mount, if the polar axis and declination axis are not exactly at right angles, east-west shifts of the image occur that are proportional to $\sin\delta$.

FORMULA :

$$\Delta h \simeq + \text{ NP } \tan\delta$$

NOTES :

NP is one of the six purely geometrical terms that affect all equatorial mounts, the others being IH, ID, CH, ME and MA.

The image displacement produced by NP is zero on the celestial equator and reaches a maximum at the pole.

Most telescope sites lie well away from the equator of the Earth and hence the correction for NP tends to be the same sign most of the time. Furthermore, because there is more sky at lower declinations than near the pole there are likely to be fewer pointing observations in a given declination-band near the pole than in a similar band nearer the equator. These two effects conspire so that the NP effect tends to be poorly sampled when pointing tests are made, and hence the NP coefficient is apt to be poorly determined. In some cases, it can be better to omit NP from the model and rely on other terms mopping up any NP-like effects that are present.

A non-zero NP on its own means there is an area around the pole inside which the telescope cannot point.

The approximate formula given above is implemented literally in the term NPL.

NPAE   Az/El non-perpendicularity   NPAE

DESCRIPTION :

In an altazimuth mount, if the azimuth axis and elevation axis are not exactly at right angles, horizontal shifts of the image occur that are proportional to $\sin E$.

FORMULA :

$$\Delta A \simeq - \ \texttt{NPAE} \ \tan E$$

(The azimuth sign convention is that $A = 0°$ is north and $A = 90°$ is east.)

NOTES :

NPAE is one of the six purely geometrical terms that affect all altazimuth mounts, the others being IA, IE, CA, AN and AW.

The image displacement produced by NPAE is zero on the horizon and reaches a maximum at the zenith.

Just as E is always positive, the correction for NPAE never changes sign. Furthermore, because there is more sky at lower elevations than near the zenith there are likely to be fewer pointing observations in a given elevation-band near the zenith than in a similar band nearer the horizon. These two effects conspire so that the NPAE effect tends to be very poorly sampled when pointing tests are made, and hence the NPAE coefficient is apt to be poorly determined. In some cases, it can be better to omit NPAE from the model and rely on other terms mopping up any NPAE-like effects that are present.

A non-zero NPAE on its own means there is an area around the zenith inside which the telescope cannot point. (This is a geometrical limitation and is distinct from the blind spot caused by velocity and acceleration limits close to the zenith.)

The approximate formula given above is implemented literally in the term NPAEL.

NRX   Nasmyth rotator displacement, horizontal   NRX

DESCRIPTION :

In a Nasmyth altazimuth mount, a horizontal displacement between the elevation axis of the mount and the rotation axis of the Nasmyth instrument-rotator produces an image shift on the sky with a horizontal component proportional to cosine elevation and an elevation component proportional to minus sine elevation.

FORMULA :

$$\Delta A = -\ \mathtt{NRX}$$

$$\Delta E = -\ \mathtt{NRX}\ \sin E$$

(The azimuth sign convention is that $A = 0°$ is north and $A = 90°$ is east.)

NOTES :

The same corrections apply even if there is no Nasmyth rotator, except that the displacement is between the elevation axis and the nominated pointing-origin in the Nasmyth focal-plane.

NRX is positive when the elevation axis emerges from the Nasmyth focal plane to the right of the rotator axis.

NRY   Nasmyth rotator displacement, vertical   **NRY**

DESCRIPTION :

In a Nasmyth altazimuth mount, a vertical displacement between the elevation axis of the mount and the rotation axis of the Nasmyth instrument-rotator produces an image shift on the sky with a horizontal component proportional to sine elevation and a vertical component proportional to cosine elevation.

FORMULA :

$$\Delta A \simeq -\ \mathtt{NRY}\ \tan E$$

$$\Delta E \simeq +\ \mathtt{NRY}\ \cos E$$

(The azimuth sign convention is that $A = 0°$ is north and $A = 90°$ is east.)

NOTES :

The same corrections apply even if there is no Nasmyth rotator, except that the displacement is between the elevation axis and the nominated pointing-origin in the Nasmyth focal-plane.

NRY is positive when the elevation axis emerges from the Nasmyth focal plane above the rotator axis.

The NRY correction has an identical form to the two terms NPAE and TF acting in combination. This unfortunately prevents simultaneous fitting of pointing observations to a model containing all three terms. The recommended procedure for Nasmyth telescopes is to determine a canonical value of TF from observations at a non-Nasmyth focus (prime, Cassegrain, Newtonian etc.) and then to fit Nasmyth pointing observations to a model which includes TF fixed at this value.

POX Pointing Origin x-coordinate **POX**

DESCRIPTION :

In the case where (a) there is an instrument rotator and (b) target images are received at a place not coincident with the rotator axis, there is said to be a *pointing origin* at coordinates $[\,x, y\,]$ in the rotating focal plane. The POX and POY terms are the x- and y-coordinates of the pointing origin.

The effects of POX and POY depend on the rotator angle, which must be provided in degrees as auxiliary reading #1 and must change during the pointing test if the pointing origin $[\,x, y\,]$ is to be fitted. The focus at which the rotator is located (fixed to the telescope, or at one of the Nasmyth or coudé foci) must also be specified.

A tangent-plane projection is assumed, and the units of POX and POY match sky coordinates at the center.

The pointing change, for example in the form ΔA and ΔE, depends on which focus is being used, and cannot be formulated generally and concisely. The pointing origin $[\,x, y\,]$ is thus different from other pointing terms, and should be seen as supplementing the pointing-model proper, the latter corresponding to the rotator axis.

POY Pointing Origin y-coordinate **POY**

DESCRIPTION :

See POX.

TF tube flexure (sine) **TF**

DESCRIPTION :

Classical tube flexure: change in zenith distance proportional to $\sin \zeta$.

FORMULA :

$$\Delta Z = +\ \texttt{TF}\ \sin Z$$

In equatorial spherical coordinates:

$$\Delta h \simeq +\ \texttt{TF}\ \cos \phi \sin h \sec \delta$$

$$\Delta \delta \simeq +\ \texttt{TF}\ (\cos \phi \cos h \sin \delta - \sin \phi \cos \delta)$$

NOTES :

This is the classic tube flexure model, which assumes that the telescope obeys Hooke's Law. In practice there is often a rapid increase in the vertical displacement towards the horizon, and it is sometimes found that a tangent law is a better approximation than a sine law: see the TX term.

TFP   AAT tube flexure supplementary term   **TFP**

DESCRIPTION :

The AAT displays a more rapid increase in vertical deflection at large zenith distances than predicted by a pure Hooke's Law tube flexure model (the term TF). The special TFP term adds a ζ^4 component, the effect of which is felt only at the lowest elevations.

FORMULA :

$$\Delta Z = + \ \texttt{TFP} \ \zeta^4$$

NOTES :

This special AAT term illustrates the observed tendency of telescopes not to be well-modeled by the expected TF term. In the case of the AAT, the size of the supplementary TFP term is noticeably dependent on which of the AAT's interchangeable top-ends is in use, whereas the main TF term is broadly independent of top-end.

TX   tube flexure (tangent)   **TX**

DESCRIPTION :

Empirical tube flexure: change in zenith distance proportional to $\tan \zeta$.

FORMULA :

$$\Delta Z = + \ \texttt{TX} \ \tan Z$$

In equatorial spherical coordinates:

$$\Delta h \simeq + \ \texttt{TX} \ \cos \phi \sin h \sec \delta \ / \ (\sin \delta \sin \phi + \cos \delta \cos h \cos \phi)$$

$$\Delta \delta \simeq + \ \texttt{TX} \ (\cos \phi \cos h \sin \delta - \sin \phi \cos \delta) \ / \ (\sin \delta \sin \phi + \cos \delta \cos h \cos \phi)$$

NOTES :

The classical tube flexure model, TF, which assumes that the telescope obeys Hooke's Law, is a sine rather than tangent law. In practice there is often a rapid increase in the vertical displacement towards the horizon, and it is sometimes found that the present term, TX, is a better approximation than TF.

Note that TX will compensate for any scaling error in the refraction corrections.

Another version of this term, TXL, is implemented directly in elevation:

$$\Delta E = - \text{ TXL } \cot E$$

It is not appropriate for the generalized gimbal, or any other case where significant azimuth axis tilt is present.

X2HC $\qquad$ cos(2h) term EW $\qquad$ **X2HC**

DESCRIPTION :

Change east-west proportional to $\cos 2h$.

FORMULA :

$$\Delta h \simeq + \text{ X2HC } \cos 2h \sec \delta$$

NOTES :

The same as the generic harmonic HXCH2 but marginally faster, this term is part of the AAT model.

ZE $\qquad$ AAT H.A. Z-gear effect on polar-axis elevation $\qquad$ **ZE**

DESCRIPTION :

ZE is an effect peculiar to the AAT: see the notes below. It takes the form of a change in polar axis elevation proportional to the first auxiliary reading.

FORMULA :

$$\Delta h \simeq + \text{ ZE} \cdot \text{aux}_1 \cdot \sin h \tan \delta$$

$$\Delta \delta \simeq + \text{ ZE} \cdot \text{aux}_1 \cdot \cos h$$

NOTES :

The AAT final drive consists of a large spur gear (the "Z-gear") at the northern end of the mounting yoke, driven by a gearbox at its lowest point. Varying upward pressure from the drive gearbox causes an unwanted rise-and-fall of the entire northern end of the mounting. This is corrected by directly measuring the rise-and-fall of the Z-gear, using an electronic displacement pickup, and injecting the readings into the pointing model. During pointing tests, the measurements are logged and find their way into the TPOINT input file as an "auxiliary reading" (the last field in the sample data file `aat15.dat`).

The principal effect of the rise-and-fall is on the hour angle encoder readouts, affecting tracking directly: see the term ZH.

This and other AAT-specific terms are included in the TPOINT package as a demonstration of what is involved in getting the best possible pointing out of a large telescope. This particular term demonstrates TPOINT's "auxiliary readings" capability; a similar approach can be used on any telescope the pointing of which is influenced by mechanical shifts or run-outs that are hard to predict but which can be measured in real-time.

ZH   AAT H.A. Z-gear effect on hour angle   **ZH**

DESCRIPTION :

ZH is an effect peculiar to the AAT: see the notes below. It takes the form of a change in hour angle proportional to the first auxiliary reading.

FORMULA :

$$\Delta h = + \; \texttt{ZH} \cdot \text{aux}_1$$

NOTES :

The AAT final drive consists of a large spur gear (the "Z-gear") at the northern end of the mounting yoke, driven by a gearbox at its lowest point. A separate gearbox, mounted to one side, drives the encoder system. Varying upward pressure from the drive gearbox causes an unwanted rise-and-fall of the entire northern end of the mounting, which affects the encoder readings and hence the tracking. This is corrected by directly measuring the rise-and-fall of the Z-gear, using an electronic displacement pickup, and injecting the readings into the pointing model. During pointing tests, the measurements are logged and find their way into the TPOINT input file as an "auxiliary reading" (the last field in the sample data file `aat15.dat`).

The rise-and-fall also affects the polar axis elevation directly: see the term ZE.

This and other AAT-specific terms are included in the TPOINT package as a demonstration of what is involved in getting the best possible pointing out of a large

telescope. This particular term demonstrates TPOINT's "auxiliary readings" capability; a similar approach can be used on any telescope the pointing of which is influenced by mechanical shifts or run-outs that are hard to predict but which can be measured in real-time.

8   THE INITIALIZATION FILES

The way TPOINT is configured can be selected at run-time by specifying which TPOINT initialization file to use. There are four ways to accomplish this:

1. The required file can be specified through the second argument of the `tpoint` command that starts up the package.

2. Failing that, a file `tpoint.ini` found the current directory (or a link with the same name) is used.

3. If no local `tpoint.ini` file is present, one can be specified through the environment variable `TPT_INI`.

4. If `TPT_INI` is not set, the standard initialization file `tpoint.ini` (the default location is `$HOME/etc/tpoint/`) is used.

8.1   The TPOINT initialization file

Here is an example `tpoint.ini` file. It contains explicit filenames; however, in the `tpoint.ini` supplied with the package, the pathnames contain the symbol `HOME`, and the actual pathname is substituted when the file is installed by `make`.

```
!
! - - - - - - - - - - -
!  t p o i n t . i n i
! - - - - - - - - - - -
!
!  Initialization file for Unix version of TPOINT
!
!  Latest revision:   13 February 2011
!
!  Copyright P.T.Wallace.  All rights reserved.
!

procedure_library        procs.dat
star_catalog             stars.dat
help_prefix
help_name                tpoint
help_suffix              .shl
graphics_device_name     tpoint
graphics_hardcopy        tpoint.ps
TPG_initialization       tpg.ini
```

```
          pen_frame              18
          pen_caption            5
          pen_axes               17
          pen_labels             12
          pen_points             13
          pen_offpoints          2
          font_caption           1
          font_labels            1
          text_precision         2
          short_reports          0
          script_abort           1
          threads                8

          end
```

The commands, which can be in any order, have the following meanings:

- The first two items specify the files containing the default star catalog and procedure library.

- The three "help" items specify the full name of the top-level help library and enable the subsidiary libraries to be found.

- The graphics device name is the default argument for the PLTON command.

- The graphics hardcopy name is the default name for the file produced when the GC command's "P" or "B" function is invoked.

- The next item points to the separate initialization file for the TPG graphics system. An example is given below.

- The next six items specify the default pen colors. The colors corresponding to the different pen numbers are specified in the TPG initialization file.

- The font numbers specify the default fonts for captions and labels.

- The text precision specifies the default text precision for all plotting.

- The short reports command allows control over the amount of output, where 0, 1 or 2 mean full, abridged, none respectively.

- The script abort command controls whether procedures are aborted as soon as an error occurs. The default is 1, meaning that scripts are aborted. 0 means procedures continue to run to completion even if errors occur.

- The `threads` item specifies how many parallel threads may be used during certain compute-intensive operations. For the best performance, the specified value should be the number of cores in the computer that is being used (or twice that if hyper threading is supported). Fewer will lead to slower results but will leave more machine resources available for other applications. Greater will waste time on per-thread software overheads, though the effect is not noticeable for slight increases.

(*n.b.* The current TPOINT implementations do not support multiple fonts or text precisions.)

8.2   The TPG (TPOINT graphics) initialization file

Here is an example `tpg.ini` file:

```
!
! - - - - - - - -
!   t p g . i n i
! - - - - - - - -
!
!  Initialization file for the TPOINT graphics subsystem
!
!  Last revision:   27 November 2010
!
!  Copyright P.T.Wallace.  All rights reserved.
!

hardcopy_file       tpoint.ps
unixshell           /usr/bin/wish
width               765

background          black
pen1                white                          ! pen 1 = white
pen2                #F00                           ! pen 2 = red
pen3                #0F0                           ! pen 3 = blue
pen4                #00F                           ! pen 4 = green
pen5                #FF0                           ! pen 5 = yellow
pen6                #F0F                           ! pen 6 = magenta
pen7                #0FF                           ! pen 7 = cyan
pen8                #000                           ! pen 8 = black
pen9                #777                           ! pen 9 = dark grey
pen10               #CCC                           ! pen 10 = light grey
pen11               #FFF                           ! pen 11 = white
pen12               #F99                           ! pen 12 = light red
```

```
    pen13               #9F9                            ! pen 13 = light green
    pen14               #99F                            ! pen 14 = light blue
    pen15               #FF9                            ! pen 15 = light yellow
    pen16               #F9F                            ! pen 16 = light magenta
    pen17               #9FF                            ! pen 17 = light cyan
    pen18               #D83                            ! pen 18 = brown

    commands:

    end
```

- The `shell` variable specifies the Tcl/Tk windowing shell to be used.

- The `width` item allows the width of the graphics window to be specified, in pixels. It will be rounded down to the nearest multiple of three, to allow an exact 3:4 aspect ratio. The value above, 765, is suitable for a laptop PC; a rather larger number may be more suitable on a full-size workstation. The window can in any case be resized dynamically using the mouse.

- The background color (choose one defined in the local X configuration and formatted in Tk style) is specified through the `background` item.

- The pen colors are defined through items `pen1-18`, in any of the Tk formats; the format used in the above example specifies colors as three hexadecimal digits which represent the red, green and blue intensities respectively.

Finally, between the `commands:` line and the `end` line, it is possible to put Tcl/Tk commands for transmission to the graphics server just after it has been created, to achieve special effects. Depending on what Tcl/Tk commands are added, it may be important to know what environment already exists by then. Here is a typical example:

```
wm protocol . WM_DELETE_WINDOW {bell}
canvas .c -width 764 -height 573 -background black \
    -selectforeground white
pack .c
wm title . tpoint
global resize_am
set resize_am 1.0
proc resize { w ww wh } {
 global resize_w0 resize_h0
 global resize_am
 set border [$w cget -bd]
 set cw [expr {$ww-2-(2*$border)}]
 set ch [expr {$wh-2-(2*$border)}]
```

```
 if { [info exists resize_w0] } {
  set amw [expr {double($cw)/$resize_w0}]
  set amh [expr {double($ch)/$resize_h0}]
  set amag [expr {$amw < $amh ? $amw : $amh}]
  set rmag [expr {$amag/$resize_am}]
  .c scale all 0 0 $rmag $rmag
  set resize_am $amag
 } else {
  set resize_w0 [expr {double($cw)}]
  set resize_h0 [expr {double($ch)}]
 }
}
bind .c <Configure> "resize %W %w %h"
pack .c -fill both -expand 1
```

9 COMMAND SUMMARY

COMMAND	FUNCTION	DEFAULT
coeff value	set and report coefficient value	report only
ADJUST T or S	select model direction	report only
APPEND ON or OFF	next observations will [not] be appended	will be appended
CALL *proc*	call library procedure *proc*	–
CAPT ON or OFF	enable/disable plotting of captions	captions enabled
CHAIN *c1 c2* etc.	selected terms are applied sequentially	whole model chained
CLIST	list current coefficients	–
CLOBBER ON or OFF	enable/disable file overwrite prompting	silent
ECHO ON or OFF	enable/disable procedure command echo	echo on
END	exit	–
FAUTO *n*	auto model to *n*th harmonic	8
FIT N	fit [or apply model without fitting]	fit
FITTOL *t*	specify and report ill-conditioning tolerance	report only
FIX *c1 c2* etc.	exclude selected terms from fit	fix all terms
FLIST *file*	write observations to a file	–
FRAME ON or OFF	enable/disable plotting of frames	frames enabled
G *y x s*	plot residuals	autoscale
GAM *t s*	look for axis misalignment	equatorial, autoscale
GC *f s*	graphics device control	clear screen
GDIST	plot distributions of residuals	–
GHYST *t s*	look for hysteresis	equatorial, autoscale
GMAP *t s*	Cartesian cylindrical plot	equatorial, autoscale
GSCAT *t r*	scatter plot	equatorial, autoscale
GSMAP *s =*	orthographic or equal-area map	autoscale, orthographic
H *r a n1 n2*	search for harmonics	–
H2 *r a1 a2 n1 n2 n3 n4*	list cross-harmonic terms	–
H2A *r a1 a2 n1 n2 n3 n4*	add best cross-harmonic term to model	–
HELP *topic*	enter HELP session	enter at top level
INDAT *file subset*	read file of observations	previous file
INMOD *file*	read model from a file	–
INPRO *file*	read library file	original library
INST *file*	read star catalog	original catalog
LOSE *c1 c2* etc.	remove selected terms from model	discard all terms
MARK *n*	set pen for MASKed observations	normal color
MARKH *h*	set marker height	0.2
MASK *q c v* etc.	flag selected observations inactive	mask all observations
MESLEV *m r*	limit messages to given severity levels	all messages
MODOR	re-order model terms	
MVET *n*	find and optionally remove weak terms	report only

NEED *c1 c2* etc.	force inclusion of nominated model terms	unfix all terms
OUTDAT *file*	write file of observations	–
OUTL *v n*	identify and optionally mask outliers	don't mask
OUTMEX *file*	write model as spreadsheet line	–
OUTMOD *file* S	write model (full or session) to a file	full
PARAL *c1 c2* etc.	terms *c1 c2* etc. are applied in parallel	whole model parallel
PENS *f c a l p o*	specify and report pens	report only
PERFCT ° ′ ″	create ideal observations	ϕ from data list
PLTOF	close plotting window	–
PLTON *label*	open new plotting window	–
PLTZ *z*	select plotting zone	use whole display surface
PROC *x*	start of library procedure *x*	–
PURGE	purge MASKed observations	–
REPLEN S or L	specify report length option	full length reports
RESET	zero coefficients and cancel corrections	–
RETURN	return from a procedure	–
SAMSIG	estimate PSD by sampling	–
SAY *string*	display message	blank line
SETCAP *string*	specify caption	caption blank
SHOW	display system parameters	–
SLIST *r* P	list the observations	list all, unpaged
SPAWN *string*	execute shell command	spawn new shell
SUBSET *subset*	MASKed observations to data subset	lose all memberships
UNFIT N	apply pointing model in reverse	current model applied
UNMARK *n*	reverse earlier MARK commands	normal color
UNMASK *q c v* etc.	flag selected observations active	unmask all observations
USE *c1 c2* etc.	include selected terms in model	unfix all terms
VT	clear the text screen	
Ctrl+C	abort current command	